

# Optical and near-infrared observations of hard serendipitous *Chandra* sources

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Received *date will be inserted by the editor*; accepted *date will be inserted by the editor*

**Abstract.** We have been carrying out a successful observational programme targeted at finding the highly obscured quasars that are thought to be the main contributors to the hard X-ray background. Out of 56 sources so far studied with optical and near-infrared imaging and spectroscopy, we have found three definite and a further twelve possible Type II quasars. Few sources show significant line emission, suggesting that the line photons are depleted by the large columns of obscuring matter. The redshift distribution of our sources shows a distinct peak at  $z \sim 1$ . The broad-band colours and magnitudes of the optical/near-infrared counterparts indicate that the light in these bands is dominated by the continuum of a massive bright galaxy.

**Key words:** cosmology: diffuse radiation – galaxies: quasars

## 1. Introduction

Standard models synthesize the hard (2–10 keV) X-ray background (hereafter HXRB) as the integrated emission from a population of obscured active galactic nuclei (AGN); the hard spectral slope is produced by the presence of large amounts of intrinsic obscuration that preferentially erode the soft photons (Setti & Woltjer 1989; Comastri et al 1995; Wilman & Fabian 1999). The models suggest that the sources with the most accretion activity are hidden as highly obscured AGN at a range of both absorbing columns and redshift. Thus a large population of powerful active objects at high redshifts is expected to be ‘missing’ from conventional (optically-based) surveys, and this regime may be where most of the growth of massive black holes occurs.

We report here on our work in progress aiming to find such absorbed powerful sources in sufficient numbers to determine the importance of their contribution to the hard X-ray background.

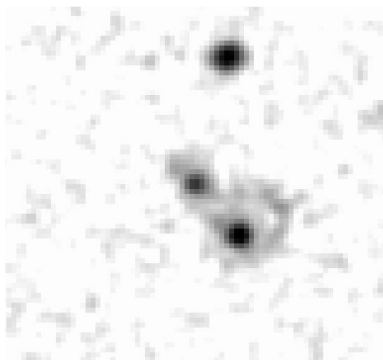
## 2. The Sample

In contrast to deep narrow surveys (eg Brandt et al 2001; Hasinger et al 2001; Giacconi et al 2002), we have undertaken a wide-area search, targeted towards finding ‘type II’ highly obscured quasars (ie objects with intrinsic  $L_X > 2 \times 10^{44}$  erg s $^{-1}$ ). We have selected X-ray sources from those

found serendipitously in the field of our own and archival *Chandra* ACIS-S observations, most of which are of clusters of galaxies (out to  $z \sim 0.5$ ). Whilst this means that the central area of the most sensitive ACIS chip is taken up by the soft thermal emission from the intracluster medium, the cores of clusters are also popular targets for optical imaging, so deep multi-wavelength images are already available from telescope archives. In addition, gravitational lensing by the foreground cluster can boost distant sources into observability (eg in A2390, Cowie et al 2001; Crawford et al 2002). [Contamination by sources within the cluster itself has not proven to be a problem, as we have only found two sources to have a redshift consistent with that of the cluster.]

We have compiled a sample so far of 341 sources with more than 10 net counts taken from 11 fields. 131 of these sources are hard, with a significant number of their counts emerging above 2 keV. At the typical 10–20 ksec exposure times of our *Chandra* observations this means we are detecting sources with fluxes of  $10^{-13}$  to  $10^{-15}$  erg cm $^{-2}$  s $^{-1}$ , straddling the ‘knee’ in the hard source counts log  $N$ -log  $S$  distribution (Rosati et al 2002). Thus in this regime we are selecting the sources which are the dominant flux contributors to the HXRB. Deeper surveys do *not* find obscured quasars in great numbers (only two have been reported: Norman et al 2002; Stern et al 2002), though they do find many Seyfert IIs (with intrinsic  $L_X < 2 \times 10^{44}$  erg s $^{-1}$ ). Due to the flattening in source counts, we should be able to detect more of the powerful sources by studying a larger number of less deep fields than would be found in a single deep field.

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**Fig. 1.**  $10'' \times 10''$   $K$ -band image of the  $K = 19$  source MS2137\_4 taken with the VLT, showing its curious double morphology with diffuse (possibly tidal) structure. The hard X-ray source is associated with the NE component of the pair, but both have a very red  $B - K$  colour. The estimated redshift is  $z_{phot} \sim 3.3$ .

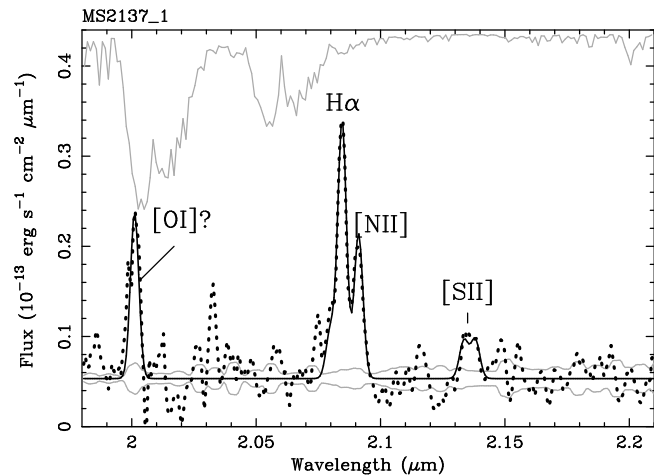
### 3. Observations

A preliminary investigation of 31 serendipitous sources in the A 2390 cluster (Crawford et al 2002) showed that the optical spectra of the X-ray hard sources fell into two broad classes: a bright population at low redshift ( $z < 0.3$ ) with strong but narrow emission lines, consistent with Compton-thick Seyfert II galaxies; and a distant ( $z > 1$ ) faint population of hard sources with very weak, or no emission lines. Two of the sources were found to be Type II quasars with obscuring columns in excess of  $N_H > 10^{23} \text{ cm}^{-2}$ , and an intrinsic bolometric luminosity  $> 10^{45} \text{ erg s}^{-1}$ ; in both cases strong gravitational lensing by the foreground cluster enhanced their detection.

As we expect our target sources to be highly redshifted ( $z > 1$ ) and/or absorbed, we moved to the near-infrared to seek counterparts for the hard X-ray sources from our full sample that are very faint (or absent) in the optical band. We imaged the fields of the sources in the  $J$ ,  $H$  and  $K$  bands, using both UKIRT and VLT. We have near-infrared detections of 56 sources to  $K < 20$ , 37 of which are hard (the soft sources were included as they happened to be in the field of view of some of the hard sources). Nearly all of the optically-faint sources are relatively bright and readily detected in the near-infrared with a median  $K$  magnitude of  $\sim 18$  (Crawford et al 2001; Gandhi et al 2002a). Most are clearly resolved, and a few have a double (possibly interacting) morphology (eg Fig 1).

We also obtained broad-band near-infrared spectra of 20 of these hard sources, again using both UKIRT and VLT (Crawford et al 2001; Gandhi et al 2002a). Only 3 sources had strong detectable line emission, and only one of these had an unambiguous redshift identification, from a clear detection of  $H\alpha$ , [NII] and [SII] at a redshift of 2.176 (Fig 2). Most of the sources had a flat continuum spectrum, showing no significant emission lines to a best limiting equivalent width of  $20\text{\AA}$ .

The lack of identifiable emission line or absorption features in our near-infrared spectra made it expedient to use photometric redshift estimation to characterize most of our

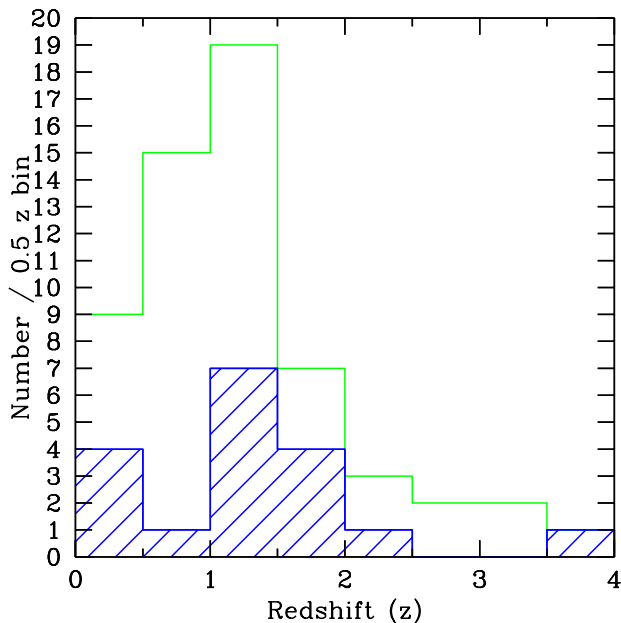


**Fig. 2.** ISAAC  $K$ -band spectrum of the source MS2137\_1 at a redshift of  $z = 2.176$ . The data are shown as bold dots, the model fitted to the emission lines as a solid line and the  $1\sigma$  errors due to the sky above and below a constant fitted continuum as the faint grey lines. Sky absorption has been rescaled to be plotted as the faint grey line at the top of the figure. The spectrum has been smoothed over 5 adjacent pixels.

source population. We used the publicly-available code HYPERZ (Bolzonella et al 2000) which is based on fitting template continua to broad-band photometric fluxes in as many bands as possible. A check of the derived  $z_{phot}$  against a measured  $z_{spec}$  (where available) in our sample found that they agree well for the hard sources; but less well for the soft sources, where there may be a larger contribution to the broad band fluxes from the (variable) quasar continuum and emission lines.

### 4. Results and Discussion

To investigate the surprising lack of significant spectral features in our near-infrared spectra of hard sources, we predicted the expected broad line strengths based on the observed correlation between the 2-10 keV X-ray luminosity and the luminosity in the broad  $H\alpha$  emission line in emission-line AGN (Ward et al 1988). In all seven targets where we have a redshift identification (or a good photometric redshift estimate), the predicted line emission is sufficiently strong that we expect to have observed broad lines above a  $2\sigma$  threshold, and in at least four cases, above a  $3\sigma$  threshold. One source (MS2137\_1; Fig 2) that is predicted to have a strong broad  $H\alpha$  line does not show this component, although the narrow component is clearly visible. Alternatively, if the estimated redshift is not known (or very wrong), it is still very unlikely that our bandpasses systematically missed any (either broad or narrow) emission lines in so many sources; there are few regions in redshift space where no redshifted lines are observed in either (or both) of the observed bandpasses (we expect Hydrogen or MgII lines to be visible for most of  $0 < z < 5$ ). We thus infer that our sources are dominated by the continuum light from the host galaxy in the near-infrared, with some mechanism inhibiting or obscuring the line emission. The lines are most likely depleted due to the



**Fig. 3.** Redshift histogram for 18 sources with spectroscopic measurements (hatched regions) and 40 additional sources with photometric redshifts only (clear outlined region).

large columns of obscuring gas and associated dust intrinsic to the sources.

The redshift distribution of the sources studied in detail so far (Fig 3) shows a distinct peak at  $z \sim 1$ , with a small tail of sources extending to higher redshift, in broad agreement with findings from follow-up on the deep fields (Rosati et al 2002; Hasinger 2002; Brandt et al 2002). Both the hard and soft sources are similarly spread in redshift. Additional evidence that the optical and near-infrared light from the counterparts of hard sources is dominated by the host galaxy comes from their broad-band colours, which are redder than those of an unobscured QSO. Some are extremely red objects, with  $R - K > 5$ . The hard sources in our sample cover the brighter region of  $K - z$  space, most having luminosities brighter than  $L^*$  at all redshifts. This suggests that they are located in very massive and bright galaxies, exactly those assumed to host some of the most massive black holes (Magorrian et al 1998; Merrit & Ferrarese 2001).

The bulk of the hard objects in our sample have X-ray column densities which classify them as type II AGN. We have been successful in identifying three *bona fide* Type II QSO (two in the field of A 2390 Crawford et al 2002; the other is shown in Fig 4 and in Gandhi et al 2002b), with high intrinsic luminosities ( $L_X > 2 \times 10^{44} \text{ erg s}^{-1}$ ) and obscuring column densities ( $N_H > 10^{23} \text{ cm}^{-2}$ ).

We have a further six sources with hard X-ray colours and an X-ray luminosity of  $L_X > 10^{45} \text{ erg s}^{-1}$  – assuming they lie at a redshift equal to or greater than their  $z_{phot}$  or  $z_{spec}$ , and have a power-law spectrum with  $\Gamma = 1.4$  – or a total of twelve such potential Type II quasars, with  $L_X > 3 \times 10^{44} \text{ erg s}^{-1}$  (eg in Fig 5). These luminosities are derived assuming only Galactic absorption; obviously the hard X-ray colours suggest the further presence of large amounts of in-

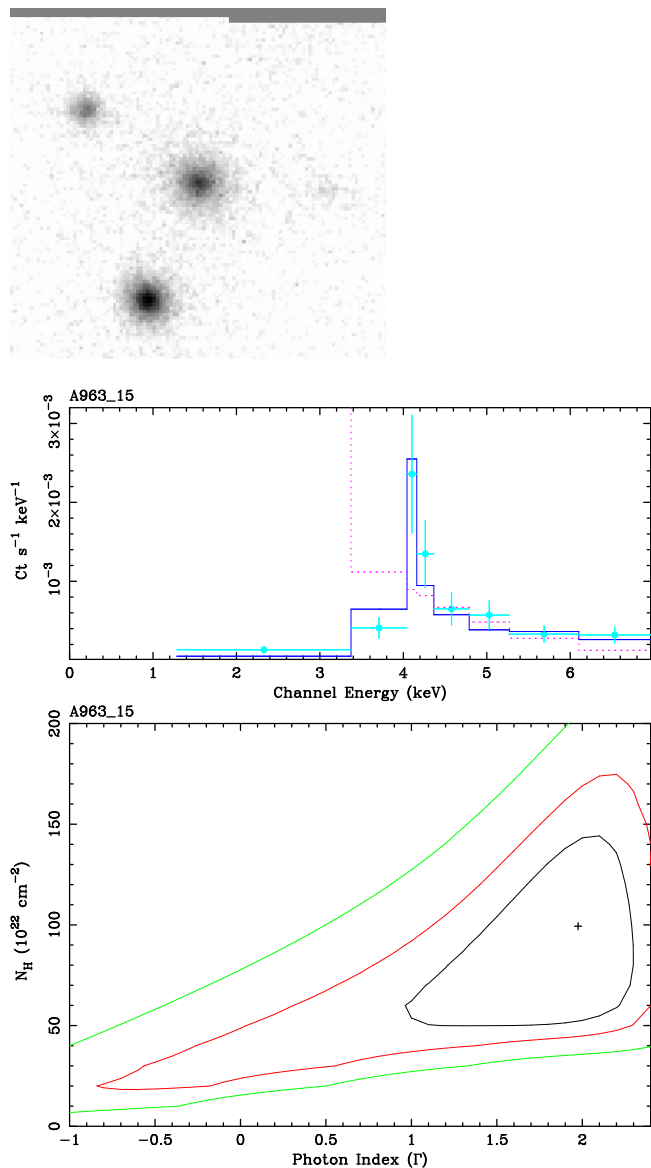
trinsic absorption that will increase the inferred luminosity. Assuming a steeper slope  $\Gamma$  will only act to increase the intrinsic column density required. Aside from A963.15 (Fig 4), the photometric redshifts of these putative Type II quasars range over  $1.3 < z < 3.4$ , and their optical magnitudes range from  $I \sim 19.5$  down to  $I > 23.6$ . Detailed follow-up observations of such sources, especially given the lack of emission line features in their spectra, will require large (8m) telescopes.

## 5. Conclusions

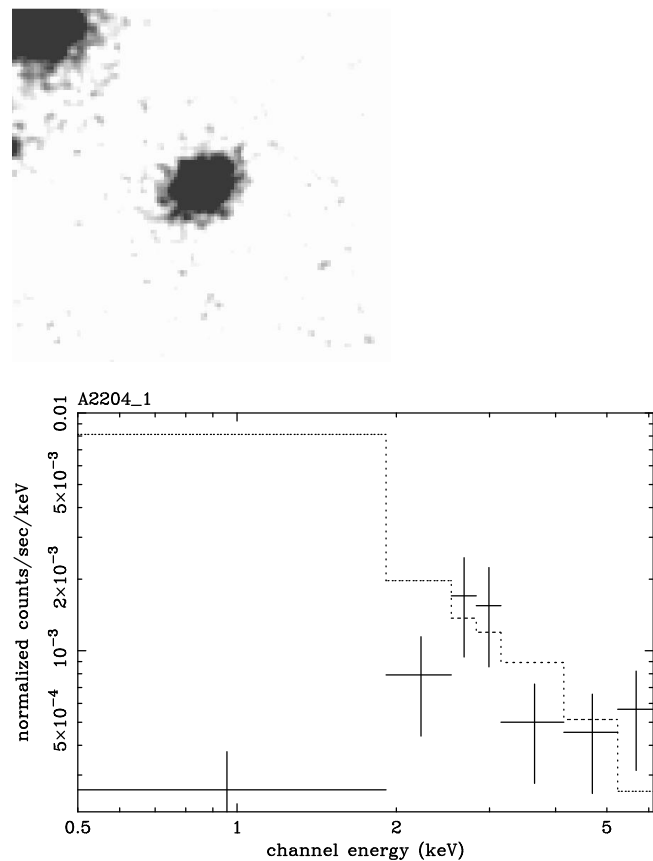
*Chandra* has been successful in detecting highly obscured AGN, even in relatively short exposures. We have a well-selected sample of three definite, and a further twelve possible, type II quasars. This number should increase as we observe further optically-faint, serendipitous hard sources from our sample.

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**Fig. 4.** (Top) UKIRT UFTI  $K$ -band image of the  $K = 16.5$  host galaxy of A963\_15, which has a photometric redshift of  $z \sim 0.56$ . The image is 10 arcsec on a side, and the target is the central object. (Middle) *Chandra* spectrum showing A963\_15 to be a very hard source, with a total flux of  $1.8 \times 10^{-14}$  erg cm<sup>-2</sup> s<sup>-1</sup>. The data (solid circles in light grey) have been fit to a power-law model (solid line) with a  $\Gamma = 2$  and a 6.4 keV Fe K $\alpha$  line at  $z = 0.54$ . The fit intrinsic absorption is  $N_H = 1.1 \times 10^{24}$  cm<sup>-2</sup>. The dotted line shows the power-law model if it were affected only by Galactic line-of-sight obscuration. (Bottom) 68, 95 and 99 per cent confidence intervals for the power-law fit, showing that the evidence for a high absorbing column is robust for all reasonable values of  $\Gamma$ .



**Fig. 5.** A  $K$ -band image (10 arcsec on a side) of the  $K = 16.4$  host galaxy associated with A2204\_1 (top) which has  $z_{phot} \sim 0.5$ . The *Chandra* X-ray spectrum (bottom) clearly demonstrates the hard nature of the source, with the least counts being detected in the soft band, where a  $\Gamma = 2$  power law model with only Galactic absorption would predict the most flux (dotted line).