MOST HARD-X-RAY–SELECTED QUASARS IN THE CHANDRA DEEP FIELDS ARE OBSCURED

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ABSTRACT

Measuring the population of obscured quasars is one of the key issues in understanding the evolution of active galactic nuclei (AGNs). With a redshift completeness of 99%, the X-ray sources detected in the Chandra Deep Field South (CDF-S) provide the best sample for this issue. In this paper, we study the population of obscured quasars in CDF-S by choosing the 4–7 keV selected sample, which is less biased by the intrinsic X-ray absorption. The 4–7 keV band–selected samples also filter out most of the X-ray-faint sources with too few counts, for which the measurements of $N_H$ and $L_X$ have very large uncertainties. Simply adopting the best-fit $L_{2–10\,\text{keV}}$ and $N_H$, we find that 71% ± 19% (20 out of 28) of the quasars (with intrinsic $L_{2–10\,\text{keV}} > 10^{44}$ ergs s$^{-1}$) are obscured with $N_H > 10^{22}$ cm$^{-2}$. Taking into account the uncertainties in the measurements of both $N_H$ and $L_X$, conservative lower and upper limits for the fraction are 54% (13 out 24) and 84% (31 out 37). In the Chandra Deep Field North, the number is 29%; however, this is mainly due to the redshift incompleteness. We estimate a fraction of $\sim 50\%$–63% after correcting for the redshift incompleteness with a straightforward approach. Our results robustly confirm the existence of a large population of obscured quasars.

Subject headings: galaxies: active — quasars: general — surveys — X-rays: galaxies

Online material: color figure

1. INTRODUCTION

Supermassive black holes (SMBHs) have been found in the center of most (if not all) nearby galaxies (e.g., Kormendy & Richstone 1995; Kormendy & Gebhardt 2001). Their growth is believed to be due mainly to the accretion of quasars (e.g., luminous active galactic nuclei) in the distant universe (Yu & Tremaine 2002). The unified model for active galactic nuclei (AGNs; Antonucci 1993) has predicted a large population of heavily obscured quasars, called type 2 quasars, which are the same as type 1 quasars but with strong obscuration in both optical and soft X-ray bands. Most of these type 2 quasars, which might dominate the black hole growth (e.g., Martínez-Sansigre et al. 2005), have been missed by optical surveys for quasars.

The hard X-ray emission is less biased by obscuration, making hard X-ray surveys a good approach to searching for type 2 quasars. Recent deep and wide-area X-ray surveys performed by Chandra and XMM-Newton have revealed a number of such sources (Norman et al. 2002; Stern et al. 2002; Mainieri et al. 2002; Fiore et al. 2003; Caccianiga et al. 2004). Using various Chandra and ASCA surveys, Steffen et al. (2003) claimed that broad-line sources dominate above $L_{2–8\,\text{keV}} = 3 \times 10^{43}$ ergs s$^{-1}$, and that type II AGNs become important only at Seyfert-like X-ray luminosities. Similarly, Ueda et al. (2003) computed the X-ray luminosity function for 2–10 keV selected AGN samples and found that the fraction of X-ray-absorbed AGNs (with $N_H > 10^{22}$ cm$^{-2}$) drops from $\sim 0.6$ at an intrinsic $L_X$ around $10^{42}$ ergs s$^{-1}$ to $\sim 0.3$ at a $L_X$ above $10^{44}$ ergs s$^{-1}$. Several other studies based on hard X-ray surveys also support the idea that the fraction of type II AGNs (or X-ray-absorbed AGNs) decreases with intrinsic luminosity (Barger et al. 2005; La Franca et al. 2005). However, contrary results are also reported. By performing Monte Carlo simulations to match the X-ray colors in the $13^\text{th}$ XMM-Newton deep field, Dwelly et al. (2005) claimed that the fraction of obscured AGNs depends on neither the luminosity nor the redshift. Perola et al. (2004) found that the fraction of obscured AGNs in the HELLAS2XMM survey does not change with X-ray luminosity, although the fraction (40%) appears to be smaller than expected (see Eckart et al. [2006] and Dwelly & Page [2006] for the most recent work in this area). Note that the observed fraction of obscured sources is a function of the X-ray flux due to the bias of the absorption and/or its evolution with redshift (see, e.g., Comastri et al. 2001; Piconcelli et al. 2002, 2003; Ueda et al. 2003; La Franca et al. 2005), and that one should therefore be cautious when comparing results from surveys with different depths.

The $2\,\text{Ms}$ Chandra exposure on the Chandra Deep Field North (CDF-N; Brandt et al. 2001; Alexander et al. 2003) and 1 Ms exposure on the Chandra Deep Field South (CDF-S; Giacconi et al. 2002) are the deepest X-ray images ever taken. Tozzi et al. (2006, hereafter T06) presented the detailed X-ray spectral studies and obtained absorption-corrected luminosities (which are essential for the identification of quasars) for the X-ray sources in CDF-S. In this paper, we present samples of the 4–7 keV band–selected AGNs in the Chandra Deep Fields and use these samples to study the population of obscured quasars. We point out that, compared to the normally used hard band (2–7/8/10 keV), the 4–7 keV band samples are less biased against X-ray photoelectric absorption and are therefore better suited to study the fraction of obscured sources. Throughout this paper, $H_0$ is taken to be $70\,\text{km}\,\text{s}^{-1}\text{Mpc}^{-1}$, $\Omega_m = 0.3$, and $\Omega_{\Lambda} = 0.7$ (Spergel et al. 2003).

2. THE X-RAY DATA REDUCTION

The 1 Ms Chandra exposure on CDF-S was composed of 11 individual ACIS observations obtained from 1999 October to
2000 December. The detailed data reduction and analysis are described in Giacconi et al. (2001, 2002), Tozzi et al. (2001), and Rosati et al. (2002). An X-ray catalog of 347 X-ray sources was presented in Giacconi et al. (2002). The 2 Ms Chandra exposure on CDF-N was composed of 20 individual ACIS observations obtained from 1999 November to 2002 February (Alexander et al. 2003). An X-ray catalog of 503 X-ray sources was presented in Alexander et al. (2003).

In this paper, we use updated X-ray data reductions with CIAO 3.2.2 and CALDB 3.1.0 on both CDF-S and CDF-N, thus including the most updated corrections. For each individual observation, the ACIS hot pixels and cosmic ray afterglows were re-identified using the new CIAO script acis_run_hotpix. The level 1 data were then reprocessed to clean the ACIS particle background for both FAINT and VFAINT mode observations, and filtered to include only the standard event grades 0, 2, 3, 4, and 6. The recently released time-dependent gain correction and ACIS charge transfer inefficiency (CTI) correction were also applied. Due to the large off-axis angle during the observations, the ACIS-S chips had poorer spatial resolution and effective area than the ACIS-I chips. In this paper, data from any ACIS-S CCD are ignored. All bad pixels and columns were also removed. High-background time intervals were finally removed from the level 2 files. The offsets between the astrometries of individual observations were obtained by registering the X-ray sources showing up in both exposures. The 4–7 keV band X-ray images were extracted from the combined event files for the two fields.

We ran wavdetect (Freeman et al. 2002) on the extracted 4–7 keV band X-ray images using a probability threshold of $1 \times 10^{-7}$ (corresponding to 0.5 false sources expected per image) and wavelet scales of 1, $\sqrt{2}$, 2, $\sqrt{2}$, 4, $4\sqrt{2}$, 8, $8\sqrt{2}$, and 16 pixels (1 pixel = 0.492 arcsec$^2$). A total of 107 X-ray sources were detected in the 4–7 keV band in CDF-S, and 176 in CDF-N. We state that no new sources were detected in addition to those in the published catalogs. Rosati et al. (2002) stated that 110 X-ray sources in CDF-S show a S/N > 2.1 in the 5–7 keV band. However, these sources are preselected by running SExtractor on the 0.5–7 keV band image and filtering with X-ray photometry measurements, and thus are not selected independently in the 5–7 keV band, but are biased by softer band brighter sources, which have a higher chance of being preselected by SExtractor. By comparing with the catalogs in Szokoly et al. (2004) and Zheng et al. (2004), we got the spectroscopic/photometric redshifts for all 107 sources in CDF-S. Of these, 54 have secure spectroscopic redshifts, and for sources with photometric redshifts, a medium uncertainty (at a 95% confidence level) of 0.17 in the redshift is expected. Considering that we are studying quasars located at much higher redshifts, the uncertainties in the redshift will not significantly affect our main results in this paper. We also make a quick estimation of the reliability of the optical counterparts. Zheng et al. (2004) provides the offsets of counterparts from X-ray positions. Taking the offsets as the radii of circles, the total area within the circles is 918 arcsec$^2$ for our 107 X-ray sources, and there are at most 7 random sources (down to R = 26, assuming a density of 100,000 deg$^{-2}$) in such a region. Considering that most X-ray sources have optical counterparts much brighter than R = 26, which could outline fainter spurious sources, and that a large fraction of them have been confirmed to be AGNs by optical spectra, the true number of spurious optical counterparts within our 107 sources is much smaller than seven, and thus will also not affect the main results presented in this paper.

Following T06, we perform X-ray spectral fitting to obtain their X-ray absorption column density and absorption-corrected rest-frame 2–10 keV luminosities. The source spectrum was extracted from a circle of radius $R_e = 2.4$FWHM, and the background was extracted from an annulus with outer radius $R_e + 12''$ and inner radius $R_e + 2''$, after masking out other sources. XSPEC 11.3.1 and Cash statistics were adopted to perform the spectral fits in the 0.6–7.0 keV band. We found that our
| XID  | Redshift | Quality | $N_H$ ($\times 10^{22} \text{ cm}^{-2}$) | $\Gamma$ | $L_{\text{2-10 keV}}$ (ergs s$^{-1}$) |
|------|----------|---------|---------------------------------|---------|--------------------------------|
own fitting results are consistent (within the fitting uncertainty; see Fig. 1) with T06, which used an earlier version of Chandra calibrations CALDB 2.26 and CIAO 3.0.1. This indicates that the uncertainty in the data calibration does not significantly affect the results presented in this paper. For the 176 X-ray sources in CDF-N, we got 127 spectroscopic/photometric redshifts from Barger et al. (2003), yielding a redshift completeness of 72%.

3. WHY 4−7 keV?

It is well known that harder band X-ray emission is less affected by photoelectric absorption; thus, the harder X-ray band is less biased against absorption and is best suited to select obscured sources (Fiore et al. 1999; Comastri et al. 2001; Nandra et al. 2003). In this paper, we choose to adopt the 4−7 keV selected sample to study the population of obscured quasars in the CDFs. Since the 4−7 keV band is less biased against the absorption than the traditional 2−7 keV band, the observed fraction of obscured quasars in this band is less biased and thus expected to be closer to the true value.

10 Note that this is not true for Compton-thick sources, since for Compton-thick absorption, even γ-ray emission could be strongly biased by Compton scattering (see Wang & Jiang 2006).
Another significant advantage of using the 4–7 keV band sample is to filter out faint sources with too few X-ray counts, for which the X-ray spectral fitting yields uncertainties that are too large and could produce artificially high absorption and luminosity (especially at high \( z \); see simulations in T06). In Figure 2, we plot \( N_H \) versus 2–7 keV band counts for the 2–7 keV selected sources in CDF-S (open squares). The 107 4–7 keV band–detected sources are plotted as filled squares. The 4–7 keV band sample picked up more sources with \( N_H \gtrsim 10^{23} \) cm\(^{-2}\) than a 2–7 keV count-limited bright sample with the same number of sources, and is thus clearly more complete for obscured sources. The 4–7 keV band sample also filters out most of the faint X-ray sources with very few counts, making it more suitable for X-ray spectral analysis.

During the spectral fit, we did not fix the photon index \( \Gamma \) at 1.8, but allowed it to vary from 1.4 to 2.4 for faint sources (since values that are too low or too high might not be physical). This is because (1), while an average \( \Gamma = 1.8 \) is valid for an AGN sample, the fitting results for individual sources could be strongly biased due to scattering of \( \Gamma \) and (2) the uncertainties in the measurements could be significantly underestimated by fixing \( \Gamma \). The fitting results are shown in Table 1. We also point out that the measurements of the intrinsic \( L_X \) have large uncertainties, especially for faint and obscured sources. In Figure 3, we plot the 90% confidence region (\( \Delta C = 2.706 \)) of \( N_H \) and \( L_X \) for two possible obscured quasars. The confidence region was calculated by varying the photon index \( \Gamma \) from 1.4 to 2.4, with the best-fit \( N_H \) and \( L_X \) marked as squares. The best-fit values with \( \Gamma \) fixed at 1.8 are plotted as circles, with 90% error bars for \( N_H \) (solid line).

4. THE FRACTION OF OBSCURED QUASARS

The output \( N_H \) versus \( L_X \) for the 107 sources selected in the 4–7 keV band in CDF-S is presented in Figure 5. Our selection criteria for obscured quasars (\( L_{2–10 \text{ keV}} > 10^{44} \) ergs s\(^{-1}\) and \( N_H > 10^{22} \) cm\(^{-2}\)) are also plotted. Among the 107 sources, we identify 13 secure obscured quasars (XID 18, 25, 27, 35, 45, 57, 62, 68, 72, 76, 153, 159, and 202) with both \( L_{2–10 \text{ keV}} > 10^{44} \) ergs s\(^{-1}\) and \( N_H > 10^{22} \) cm\(^{-2}\) at a >90% confidence level and 6 secure...
unobscured quasars (XID 11, 22, 42, 60, 67, and 206). There are 5 more quasars (XID 6, 7, 24, 31, and 61) with $L_{2-10 \text{ keV}} > 10^{44} \text{ ergs s}^{-1}$ at a >90% confidence level, but a 90% $N_H$ uncertainty range across 10$^{22}$ cm$^{-2}$. A conservative lower limit in the fraction of X-ray obscured quasars (with $N_H > 10^{22} \text{ cm}^{-2}$) is thus 54%. Considering that there are 13 possible obscured quasars with a 90% $L_{2-10 \text{ keV}}$ uncertainty range across 10$^{44} \text{ ergs s}^{-1}$ (12 with $N_H > 10^{22} \text{ cm}^{-2}$ at a >90% confidence level: XID 51, 54, 152, 156, 209, 227, 243, 253, 259, 263, 543, 601, and 609), the upper limit of the fraction could be 84%. We can clearly see that due to the large uncertainties in the measurement of both $N_H$ and $L_{2-10 \text{ keV}}$, the fraction of obscured quasars in CDF-S ranges from 54% to 84%. If we simply adopt the best-fit $N_H$ and $L_{2-10 \text{ keV}}$, the fraction is 71% (20 out 28). Applying the same selection criteria to Table 1 in T06 (with best-fit $N_H > 10^{22} \text{ cm}^{-2}$ and $L_{2-10 \text{ keV}} > 10^{44} \text{ ergs s}^{-1}$), we obtain a slightly higher fraction of 85% (39 out 46, but consistent within 1 σ uncertainty). Considering that most of our 4–7 keV band–selected sources are among the brightest in the CDF-S sample (see Fig. 2), and since the absorbed fraction is increasing at lower fluxes, the two values agree well.

Among the 13 secure obscured quasars and 18 extra possible obscured quasars, we find optical classifications for 19 of them from Szokoly et al. (2004). Only three (XID 24, 62, and 68) are classified as broad-line AGNs, and all of them show associated absorption systems in their optical spectra (XID 62 is identified as a BAL QSO), suggesting an outflow origin for their X-ray obscuration. This indicates that most of our X-ray-obscured quasars are likely type II QSOs with the broad-line region also obscured.

In CDF-N, we obtained 21 quasars with best-fit $L_{2-10 \text{ keV}} > 10^{44} \text{ ergs s}^{-1}$, 6 of which have best-fit $N_H > 10^{22} \text{ cm}^{-2}$, corresponding to a much smaller fraction of 29%. However, we note that the total number of quasars in CDF-N (21) is much less than that in CDF-S (28), although CDF-N is twice as deep and is expected to detect more quasars. This is a consequence of the fact that a significant fraction of the quasars have no available redshift. In Figure 6, we plot the redshift distribution of the 4–7 keV band sources in CDF-S and CDF-N. Assuming that the CDF-N sample has similar redshift distribution to that of the CDF-S sample, we can see in the figure that most of the sources without redshifts in CDF-N should be located at redshifts between 1 and 4. Assuming all sources without redshifts in CDF-N are located at $z = 2$ (or 3), we perform spectral fitting to estimate their $N_H$ and $L_{2-10 \text{ keV}}$. After such a coarse correction to redshift incompleteness, we find that the fraction of obscured quasars could increase to 50% (or 63%) and that the total number of quasars could increase to 31 (or 41).

5. CONCLUSIONS

We present 4–7 keV band–selected sources in CDF-S. We find that 54%–84% of the 4–7 keV band quasars in CDF-S are obscured with $N_H > 10^{22} \text{ cm}^{-2}$. This result agrees well with that of Dwelly & Page (2006), who find that~75% of XMM-Newton sources in CDF-S are obscured at all luminosities. We also note that a more recent work by Georgantopoulos et al. (2006) obtained a similar fraction of X-ray obscured quasars in CDF-S (74%, 17 out of 23) by fitting the X-ray spectra of 186 2–10 keV band–detected sources covered by all 11 Chandra pointings. We indicate that using different versions of Chandra calibrations yields consistent fitting results, suggesting that calibration uncertainty would not significantly affect the main results presented in this paper. The uncertainties in the measurement of both $L_X$ and $N_H$ are also carefully taken into account. We note that AGNs’ X-ray spectra are often more complicated than an absorbed power-law model (T06), especially in the soft band (such as warm absorber and soft excess); however, we also note that most of the quasars are located at high redshift ($z > 1$), for which extra soft features would have been shifted out of the Chandra bandpass. In CDF-N, the fraction is much lower (29%); however, we found...
that this is probably due to the redshift incompleteness in the CDF-N sample. After correcting for the redshift incompleteness, we found that 50%–63% of the quasars in CDF-N are obscured, consistent with that in CDF-S (54%–84%). Our results robustly confirm the existence of a large population of obscured quasars.

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