IDENTIFYING HIGH-REDSHIFT ACTIVE GALACTIC NUCLEI USING X-RAY HARDNESS
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ABSTRACT

The X-ray color (hardness ratio) of optically undetected X-ray sources can be used to distinguish obscured active galactic nuclei (AGNs) at low and intermediate redshift from viable high-redshift (i.e., \( z > 5 \)) AGN candidates. This will help determine the space density, ionizing photon production, and X-ray background contribution of the earliest detectable AGNs. High-redshift AGNs should appear soft in X-rays, with hardness ratio \( HR \approx -0.5 \), even if there is strong absorption by a hydrogen column density \( N_H \) up to \( 10^{23} \) cm\(^{-2} \), simply because the absorption redshifts out of the soft X-ray band in the observed frame. Here the X-ray hardness ratio is defined as \( HR = (H - S)/(H + S) \), where \( S \) and \( H \) are the soft and hard band net counts detected by Chandra. High-redshift AGNs that are Compton thick (\( N_H \approx 10^{24} \) cm\(^{-2} \)) could have \( HR \approx 0.0 \) at \( z > 5 \). However, these should be rare in deep Chandra images, since they have to be \( \approx 10 \) times brighter intrinsically, which implies a \( \approx 100 \) times drop in their space density. Applying the hardness criterion (\( HR < 0.0 \)) can filter out about 50\% of the candidate high-redshift AGNs selected from deep Chandra images.

Subject headings: galaxies: active — galaxies: high-redshift — X-rays: galaxies

1.INTRODUCTION

In the past few years, many deep Chandra images of the extragalactic sky have been obtained, with the 2 Ms Chandra Deep Field–North (CDF-N; e.g., Alexander et al. 2003) and 1 Ms Chandra Deep Field–South (CDF-S; Giacconi et al. 2002; Rosati et al. 2002) being the two deepest. Combining such exposures with deep optical images allows easy selection of candidate high-redshift (i.e., \( z > 5 \)), hereafter high-\( z \) active galactic nuclei (AGNs). Such high-\( z \) AGNs are extremely faint in optical bands blueward of the Ly\( \alpha \) wavelength, because of the heavy absorption of UV light by the high-redshift intergalactic medium (e.g., Fan et al. 2001). Optically undetected X-ray sources are thus good candidates for high-redshift AGNs. Their space density provides an upper limit on the density of high-\( z \) AGNs and can help determine their cosmological evolution and contribution to reionization (e.g., Alexander et al. 2001; Barger et al. 2003a; Koekemoer et al. 2004; Wang et al. 2004). However, the absence of these candidates in optical bands makes them difficult to identify spectroscopically. This motivates different approaches to studying them. Currently, the efforts focus mainly on their infrared colors (e.g., Yan et al. 2003; Koekemoer et al. 2004).

In this Letter, we point out for the first time that the X-ray hardness ratio can be used to filter out low-\( z \) sources from these X-ray-selected, optically undetected high-\( z \) candidates. High-\( z \) AGNs cannot be hard in Chandra images, because the absorption that makes the X-ray spectra harder is redshifted out of the soft X-ray band in the observed frame. In § 2, we present detailed simulations to quantify this effect. Here the hardness ratio (HR) is defined as \( (H - S)/(H + S) \), where \( S \) and \( H \) are the soft (0.5–2.0 keV) and hard (2.0–8.0 keV)\(^4 \) X-ray band net counts detected by Chandra.

2. SIMULATIONS

The X-ray spectra of low- and intermediate-redshift AGNs have been well studied using the observations from several generations of X-ray satellites, including Einstein, ROSAT, ASCA, BeppoSAX, Chandra, and XMM. For type 1 AGNs (i.e., Seyfert 1 galaxies and QSOs), the basic component of their X-ray spectra is a power law with photon index \( \Gamma \approx 1.9 \) (e.g., Nandra et al. 1997; George et al. 2000, Malizia et al. 2003) and an exponential cutoff at high energies (\( \approx 200 \) keV; see Malizia et al. 2003). For type 2 AGNs (i.e., Seyfert 2 galaxies and type 2 QSOs), the power law is cut off at low energies by photoelectric absorption, and the cutoff energy increases with the column density of the intercepted torus (e.g., Turner et al. 1997a; Norman et al. 2002). Recent Chandra observations show that the X-ray spectra of QSOs (i.e., luminous AGNs) at \( z \approx 4.0–6.3 \) are also well fitted by a power law with photon index \( \Gamma \approx 1.9 \) (Vignali et al. 2004). This indicates that although the space density of AGNs varies significantly from \( z \approx 0 \) to 6, the shape of their intrinsic X-ray spectra evolves relatively little. Evidence for warm absorbers and/or soft excess emission (e.g., Krolik & Kriss 2001; Piro et al. 1997) has also been found in significant numbers of AGNs. However, at high-\( z \), these features shift out of Chandra’s soft band.

In this section we present simulations to predict the X-ray colors in Chandra images for high-\( z \) AGNs by assuming a power-law spectrum (\( \Gamma = 1.9 \)) with different absorption column densities (\( N_H = 10^{21}, 10^{22}, 10^{23}, \) and \( 10^{23} \) cm\(^{-2} \), respectively; see Fig. 1 for the model spectra). We used XSPEC 11.0.1 to do the simulations and model wabs in XSPEC, a photoelectric absorption using Wisconsin cross sections (Morrison & McCammon 1983), to simulate the neutral absorption in the rest frame. The Chandra ACIS on-axis instrument response for

\(^4 \) In some papers, only the 2.0–7.0 keV band net counts were given (e.g., Giacconi et al. 2002; Stern et al. 2002; Wang et al. 2004). The difference of the HRs using different hard bands (2.0–8.0 or 2.0–7.0 keV) is negligible (\( \Delta HR < 0.008 \) from our simulations). This is actually expected because Chandra has a much lower effective area above 7 keV, and the 7.0–8.0 keV X-ray net count makes a very small contribution to the whole hard band.
CDF-S (Giacconi et al. 2002) was used, and the Galactic H I column density ($N_{\text{HI}} = 0.8 \times 10^{20}$ cm$^{-2}$) in CDF-S was taken into account during the simulations. The output X-ray HRs are plotted in Figure 2. We can see that the predicted HR is a constant ($-0.58$ for $\Gamma = 1.9$) for AGNs without intrinsic absorption at any redshift because of the power-law shape of the X-ray spectrum. The corresponding HR for different photon indices is also shown in Figure 2. While the photon index for QSOs varies from 1.5 to 3.0 (e.g., George et al. 2000), the dominant source of variation in the HR is absorption. We show in Figure 2 that an extreme power law with $\Gamma = 1.5$ would still give a soft color (HR $= -0.41$). For AGNs with intrinsic absorption, the predicted HR varies with redshift: at lower redshift, the X-ray spectra are much harder because the soft X-ray emission is significantly attenuated by the absorber, but at $z > 5$, we barely see differences between the X-ray HRs of X-ray spectra with absorption up to $N_{\text{HI}} = 10^{23}$ cm$^{-2}$, because the absorption has largely redshifted out of the soft X-ray band. If the absorber is Compton thick ($N_{\text{HI}} \geq 10^{24}$ cm$^{-2}$), even the hard X-ray emission would be significantly attenuated. At $z > 5$, the predicted HR is $\sim 0.0$. In the Compton-thick regime ($N_{\text{HI}} = 10^{24}$ cm$^{-2}$), further correction to photoelectric absorption is needed because of Compton scattering (see Matt et al. 1999; Yaqoob 1997). On the basis of Figure 3 of Matt et al. (1999), which includes Compton scattering, we conclude that the shape of the transmitted curve is unchanged by Compton scattering, while the amplitude decreases by a factor of 1.7.

For higher column density ($N_{\text{HI}} > 10^{24}$ cm$^{-2}$), the direct X-ray emission is strongly attenuated, and the X-ray spectra are dominated by a reflection component from cold and neutral gas (e.g., Turner et al. 1997b). We used the XSPEC model pexrav (Magdziarz & Zdziarski 1995) to simulate such pure reflection spectra. The Fe K emission line at 6.4 keV has a higher equivalent width (EW) in the reflection-dominated X-ray spectra of AGNs (e.g., Ghisellini et al. 1994; Levenson et al. 2002) since the direct component is absent. Therefore we add an Fe K emission line at 6.4 keV with EW of 1 keV in the rest frame, which is normal in the reflection-dominated X-ray spectra of AGNs (e.g., Levenson et al. 2002).

3. DISCUSSION

The X-ray spectra of AGNs at low to intermediate redshifts can be extremely hard because of heavy absorption (with HRs up to HR $\sim 1.0$). However, they are much softer at higher redshift because the absorbed energy shifts out of the observed bands (see Fig. 2 for simulations and Fig. 12 of Szokoly et al. 2004 for the HR distribution of a large sample of AGNs from $z = 0$ to 4). AGNs at $z \geq 5$ with intrinsic absorption up to $N_{\text{HI}} = 10^{23}$ cm$^{-2}$ should have HR $\sim -0.5$, and the Compton-thick ones ($N_{\text{HI}} \geq 10^{24}$ cm$^{-2}$) should have HR $\leq 0.1$. Because of heavy absorption and Compton scattering, the X-ray flux of Compton-thick AGNs ($N_{\text{HI}} \sim 10^{23}$ cm$^{-2}$) is attenuated by a factor of 9.5 (see Fig. 1).

For pure reflection spectra, the attenuation is even larger: assuming a reflection efficiency of 3% in the rest-frame 2.0–10.0 keV band (e.g., see Norman et al. 2002) yields a factor of 21. Thus any high-redshift sources detected with a large HR would have intrinsic X-ray luminosity of $\sim 10^{45}$ ergs s$^{-1}$. We

$^5$ Using slightly different Galactic H I column density or Chandra on-axis instrument response calculated for other ACIS-I fields does not affect any results presented in this Letter.
know that brighter QSOs are much rarer; according to the X-ray luminosity function of AGNs (e.g., see Miyaji et al. 2001; Ueda et al. 2003), a 10-fold increase in luminosity implies a 100-fold drop in the space density. Furthermore, there is evidence that the fraction of type 2 AGNs decreases at higher intrinsic luminosity (e.g., Steffen et al. 2003; Ueda et al. 2003). We conclude that those candidates with HR $\geq 0.0$ are statistically unlikely to be at $z \approx 5$. They are either obscured AGNs or QSOs at low to intermediate redshift.

*Chandra* has detected a number of AGNs at high redshift. Currently, there are 66 AGNs at $z > 4$ detected by *Chandra* ACIS, and 41 of them have published soft (0.5–2.0 keV) and hard (2.0–8.0 keV) band net counts (or 0.5–2.0 and 0.5–8.0 keV band net counts; Alexander et al. 2003; Barger et al. 2002; Brandt et al. 2001, 2002; Castander et al. 2003; Vignali et al. 2001, 2003a, 2003b; Bassett et al. 2004). All of the 41 sources have HR $\leq 0.0$, with an average value of $-0.60 \pm 0.21$, in excellent agreement with our estimates above. All of these sources are type 1 AGNs, and most of them are optically selected. Since strong X-ray emission is expected from both type 1 and type 2 AGNs, we expect the X-ray–selected high-$z$ AGN sample to include both types. However, we argue that the HR distribution of the X-ray–selected high-$z$ AGNs should be similar to that of the known $z > 4$ AGNs based on the following reasons: (1) the three X-ray–selected AGNs with $z > 4$ have consistent soft X-ray colors with the rest; (2) high-$z$ type 2 AGNs with $N_H$ up to $10^{23}$ cm$^{-2}$ are also expected to be X-ray soft with HR $\sim -0.5$; and (3) type 2 AGNs with extremely high X-ray–to–optical ratios and red colors ($\sim 15$ K). These sources might be located at $z > 6$ such that even their Ly$\alpha$ emission is redshifted out of the bandpass of ACS $z_{850}$ filter. We find that three of the seven sources have

**TABLE 1**

| ID*       | R.A. (J2000.0) | Decl. (J2000.0) | HR* |
|-----------|---------------|----------------|-----|
| Koekemoer et al. (2004) |
| 66        | 03 22 08.39   | 27 40 47.0      | 0.30$^{+0.07}_{-0.09}$ |
| 69        | 03 22 08.89   | 27 44 24.3      | -0.71$^{+0.06}_{-0.02}$ |
| 93        | 03 22 13.92   | 27 50 00.7      | -0.32$^{+0.04}_{-0.04}$ |
| 133       | 03 22 20.36   | 27 42 28.5      | -0.01$^{+0.01}_{-0.01}$ |
| 161       | 03 22 25.83   | 27 51 20.3      | -0.29$^{+0.01}_{-0.01}$ |
| 191       | 03 22 33.14   | 27 52 05.9      | -0.35$^{+0.04}_{-0.04}$ |
| 216       | 03 22 51.64   | 27 52 12.8      | -0.15$^{+0.02}_{-0.02}$ |
| Yan et al. (2003) |
| 98        | 03 22 14.67   | 27 44 03.4      | 0.09 |
| 140       | 03 22 22.44   | 27 45 43.9      | -0.39$^{+0.03}_{-0.01}$ |
| 188       | 03 22 32.17   | 27 46 51.4      | 0.39$^{+0.01}_{-0.01}$ |
| 214       | 03 22 38.03   | 27 46 26.2      | -0.45$^{+0.07}_{-0.08}$ |
| 222       | 03 22 39.06   | 27 44 39.1      | -0.11$^{+0.10}_{-0.10}$ |

Note: Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

* X-ray source ID in Giaconi et al. (2002).
* The X-ray net counts in different bands used to calculate HR are from Alexander et al. (2003). We subtract the soft band net counts from the total band (0.5–8.0 keV) net counts to calculate the hard band net counts for sources with only upper limits of the hard band net counts in Alexander et al. Errors for this quantity are calculated following the “numerical method” described in § 1.7.3 of Lyons (1991).
* Also included by Yan et al. (2003).
* Only the 0.5–8.0 keV band net count is available in Alexander et al., and the HR is derived using the upper limit of the soft and hard band counts, the sum of which is very close to the total count (32.2 vs. 27.9).

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Fig. 3.—X-ray HR distributions of 41 *Chandra*-detected $z > 4$ AGNs ($z > 4$), 19 high-$z$ candidates in the LALA Bootes field, 12 CDF-S sources in Koekemoer et al. (2004) and Yan et al. (2003), and 31 CDF-N sources discussed in Berger et al. (2003a). The three distributions are significantly different from the first one at the level greater than 99.99% based on the K-S test. See the text for details.
HR $\geq 0.0$, indicating that their X-ray colors are too hard to be at $z > 6$. These three sources could instead be type 2 AGNs at low to intermediate redshift. Their nuclear optical emission should be heavily obscured, and their host galaxies need to be substantially underluminous, or dust-obscured, compared to other known sources (Koekemoer et al. 2004). This confirms that there is a population of AGNs at low to intermediate redshift that are extremely red, with high X-ray-to–optical ratios, and undetected at the depth of GOODS. The analogous sample among nonactive galaxies is the population of extremely red objects, which have surface density comparable to Lyman break galaxies but a much lower typical redshift (e.g., Väisänen & Johansson 2004).

Using deep multicolor optical data, Barger et al. (2003a) searched candidate $z > 5$ AGNs in the 2 Ms X-ray exposure of the CDF-N and found that besides the one X-ray source spectroscopically confirmed at $z = 5.19$, only 31 X-ray sources with $z' > 25.2$ and no $B$- or $V$-band detection could lie at $z > 5$. Barger et al. (2003b) provided multiband photometry for the CDF-N X-ray sources, which allows us to identify the 31 candidate high-$z$ AGNs. The HR distribution of the 31 sources is plotted in Figure 3. Fifteen of the 31 sources have HR > 0.0 and thus cannot have $z > 5$. This directly supports the deduction that the majority of the optically undetected X-ray sources are extreme examples of the optically faint X-ray source population, most of which are obscured AGNs at $z \lesssim 3$ (Alexander et al. 2001). Barger et al. (2003a) pointed out that Haiman & Loeb (1999) overestimated the surface density of $z > 5$ AGNs by at least an order of magnitude, and similar conclusions can be seen in Alexander et al. (2001) and Szokoly et al. (2004). Our analyses indicate that applying the X-ray HR cutoff (HR > 0.0) could further reduce the surface density of candidate $z > 5$ AGNs and strengthen the above conclusions by a factor of 2. This also supports the statement that AGNs made little contribution to the reionization at $z \sim 6$ (Barger et al. 2003a; also see Dijkstra et al. 2004; Moustakas & Immler 2004).

4. CONCLUSIONS

In this Letter we present detailed simulations showing that high-$z$ AGNs cannot be hard in Chandra images since X-ray absorption will shift out of the soft band at high redshift. High-redshift AGNs should appear soft in X-rays, with HR $\sim -0.5$ at $z \gtrsim 5$, even if there is strong absorption with $N_{\text{H}}$ up to $10^{23} \text{ cm}^{-2}$. High-$z$ AGNs that are Compton thick ($N_{\text{H}} \gtrsim 10^{24} \text{ cm}^{-2}$) could have HR $\sim 0.0$. However, these should be rare in deep Chandra images, since they have to be $\gtrsim 10$ times brighter intrinsically, which implies a $\approx 100$ times drop in their space density. Most optically undetected X-ray sources with HR $\geq 0.0$ should be obscured AGNs at low to intermediate redshift. Applying the hardness criterion (HR < 0.0) can filter out about 50% of the candidate high-redshift AGNs selected from deep Chandra images. This criterion can thereby help us to understand the nature of these Chandra X-ray sources, put additional robust constraints to the space density of high-$z$ AGNs, and significantly reduce the expensive telescope time needed to spectroscopically confirm high-$z$ AGN samples based on deep Chandra images.

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REFERENCES

Alexander, D. M., et al. 2001, AJ, 122, 2156
———. 2003, AJ, 126, 539
Barger, A. J., et al. 2002, AJ, 124, 1839
———. 2003a, ApJ, 584, L61
———. 2003b, AJ, 126, 632
Bassett, L. C., Brandt, W. N., Schneider, D. P., Vignali, C., Charts, G., & Garrimere, G. P. 2004, AJ, 128, 523
Brandt, W. N., et al. 2001, AJ, 122, 1
———. 2002, ApJ, 569, L5
Castander, F. J., Freister, E., Maccarone, T. I., Coppi, P. S., Maza, J., Zepf, S. E., & Gusein, R. 2003, AJ, 125, 1689
Dijkstra, M., Haiman, Z., & Loeb, A. 2004, ApJ, in press (astro-ph/0403078)
Fan, X. et al. 2001, AJ, 121, 54
George, I. M., Turner, T. J., Yaqoob, T., Netzer, H., Laor, A., Mushotzky, R. F., Nandra, K., & Takahashi, T. 2000, ApJ, 531, 52
Ghisellini, G., Haardt, F., & Matt, G. 1994, MNRAS, 267, 743
Giacconi, R., et al. 2002, ApJS, 139, 369
Haiman, Z., & Loeb, A. 1999, ApJ, 521, L9
Koekemoer, A. M., et al. 2004, ApJ, 600, L123
Krolik, J. H., & Kriss, G. A. 2001, ApJ, 561, 684
Levenson, N. A., Krolik, J. H., Zucchi, P. T., Heckman, T. M., Weaver, K. A., & Awaki, H. 2002, ApJ, 573, L81
Lyons, L. 1991, Data Analysis for Physical Science Students (Cambridge: Cambridge Univ Press)
Magdziarz, P., & Zdziarski, A. 1995, MNRAS, 273, 837
Malizia, A., Bassani, L., Stephen, J. B., & Di Cocco, G. 2003, ApJ, 589, L17
Matt, G., Pompilio, F., & La Franca, F. 1999, NewA, 4, 191
Miyaji, T., Hasinger, G., & Schmidt, M. 2001, A&A, 369, 49

Morrison, R., & McCammon, D. 1983, ApJ, 270, 119
Moustakas, L. A., & Immler, S. 2004, ApJ, submitted (astro-ph/0405270)
Nandra, K., George, I. M., Mushotzky, R. F., Turner, T. J., & Yaqoob, T. 1997, ApJ, 477, 602
Norman, C. et al. 2002, ApJ, 571, 218
Piro, L., Matt, G., & Ricci, R. 1997, AAS, 126, 525
Rhoads, J. E., et al. 2003, AJ, 125, 1006
Rosati, P., et al. 2002, ApJ, 566, 667
Steffen, A. T., Barger, A. J., Cowie, L. L., Mushotzky, R. F., & Yang, Y. 2003, ApJ, 596, L23
Stern, D., et al. 2002, AJ, 123, 2223
Szokoly, G. P., et al. 2004, ApJS, 155, 258
Turner, T. J., George, I. M., Nandra, K., & Mushotzky, R. F. 1997a, ApJS, 113, 23
———. 1997b, ApJ, 488, 164
Ueda, Y., Akiyama, M., Ohta, K., & Miyaji, T. 2003, ApJ, 598, 886
Yäsinen, P., & Johansson, P. H. 2004, A&A, 421, 821
Vignali, C., Brandt, W. N., & Schneider, D. P. 2004, in AGN Physics with the Sloan Digital Sky Survey, ed. G. T. Richards & P. B. Hall (San Francisco: ASP), in press (astro-ph/0310656)
Vignali, C., Brandt, W. N., Schneider, D. P., & Garmire, G. P., & Kaspi, S. 2003a, AJ, 125, 418
Vignali, C., et al. 2001, AJ, 122, 2143
———. 2003b, AJ, 125, 2876
Wang, J. X., et al. 2004, AJ, 127, 2136
Yan, H., Windhorst, R. A., Röttgering, H. J. A., Cohen, S. H., Odewahn, S. C., Chapman, S. C., & Keel, W. C. 2003, ApJ, 585, 67
Yaqoob, T. 1997, ApJ, 479, 184