THE IRON LINE BACKGROUND

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ABSTRACT

We investigate the presence of iron line emission among faint X-ray sources identified in the 1 Ms Chandra Deep Field–South and in the 2 Ms Chandra Deep Field–North. Individual source spectra are stacked in seven redshift bins over the range z = 0.5–4. We find that iron line emission is a ubiquitous property of X-ray sources up to z ≈ 3. The measured line strengths are in good agreement with those expected by simple pre-Chandra estimates based on X-ray background synthesis models. The average rest-frame equivalent width of the iron line does not show significant changes with redshift.

Subject headings: galaxies: active — surveys — X-rays: diffuse background — X-rays: galaxies — X-rays: general

Online material: color figures

1. INTRODUCTION

It was pointed out already a decade ago (Matt & Fabian 1994) that prominent spectral features, and especially the ~6.4 keV iron Kα emission line commonly found in Seyfert spectra (Nandra & Pounds 1994), may lead active galactic nucleus (AGN) synthesis models to predict a detectable signature in the spectrum of the cosmic X-ray background (XRB) around a few keV. The integrated contribution of iron line emission in the sources making the XRB has been quantitatively estimated by Gilli et al. (1999), on the basis of a large database of observational results available in the pre-Chandra and XMM-Newton era. The predicted shape of the integrated emission from individual lines was computed following the prescriptions of the XRB synthesis model of Comastri et al. (1995), resulting in a rather broad bump extending from about 1 keV (depending on the maximum redshift assumed) up to 6.4 keV. The expected intensity of such a bump above the XRB level is below the 5% level over most of the energy range and reaches a maximum value of the order of 7% around 2–3 keV, the exact value being dependent on the redshift (z_{red}) at which the evolution of the luminosity function is stopped. Although such an estimate is model dependent, Gilli et al. (1999) concluded that it can be safely regarded as an upper limit to the total iron line contribution.

In the last few years, our knowledge of the XRB sources has been significantly improved by deep Chandra and XMM-Newton surveys. A fraction as large as 80%–90% of the XRB flux below 5–6 keV has been resolved into individual sources (Worsley et al. 2004). Extensive multiwavelength follow-up observations have clearly established that the X-ray source redshift distribution peaks at z = 0.7–1 (e.g., Hasinger 2004; Gilli 2004) and that about 60% of the XRB originates at z < 1 (Barger et al. 2003). In the XRB synthesis model worked out by Gandhi & Fabian (2003), the iron line contribution turned out to be maximum at about 3.8 keV (corresponding to a typical redshift of 0.7) and the excess due to the iron line is of the order of 3%–4%.

Despite the increasing number of independent observations of the XRB spectrum below 10 keV with BeppoSAX (Vecchi et al. 1999), XMM-Newton (De Luca & Molendi 2004), and the Rossi X-Ray Timing Explorer (Revnivtsev et al. 2003), yielding good signal-to-noise ratio measurements of the extragalactic background, the accuracy reached so far is not such to detect the iron features at the level expected by the model predictions outlined above.

An alternative approach, devised to avoid the line smearing due to the large redshift range over which AGN spectra are summed and the present uncertainties in the XRB spectrum, is to search for iron features over appropriate redshift bins. The detection of an iron line and the study of its intensity and profile would open the possibility of investigating interesting issues such as the metal abundances and the relative fraction of Compton-thick sources (which are known to have extremely strong iron lines) at high redshift, along with relativistically broadened lines beyond the local universe (Comastri et al. 2004; Streblyanska et al. 2005). In the following, we present and discuss the results obtained for a large sample of spectroscopically identified sources in the X-ray surveys that resolved most of the XRB: the 2 Ms pointing in the Chandra Deep Field–North (CDF-N; Alexander et al. 2003) and the 1 Ms observation of the Chandra Deep Field–South (CDF-S; Giacconi et al. 2002). Throughout this Letter, the adopted values for the Hubble constant and the cosmological parameters are H_{0} = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}, \Omega_{\Lambda} = 0.7, \text{ and } \Omega_{\text{m}} = 0.3.

2. DATA ANALYSIS

2.1. The Sample

The optical spectroscopic and photometric redshifts of the X-ray sources detected in the CDF-N are presented by Barger et al. (2003), while a list of spectroscopic redshifts of the sources detected in the CDF-S is reported in Szokoly et al. (2004, hereafter S04). Photometric redshifts based on good-quality Hubble Space Telescope/Advanced Camera for Surveys images and deep ISaac/Flat Field/Advanced Camera for Surveys images and deep ISAAC/VLT observations are available for all but four CDF-S sources without spectroscopic redshift (Zheng et al. 2004, hereafter Z04), leading to a virtually complete catalog of identified
X-ray sources. Here we have considered only those CDF-S photo-$z$ with a quality flag greater than 0.5 (see Z04 for details), ensuring a reliable redshift estimate. Moreover, given that both S04 and Z04 identifications are based on the X-ray source catalog of Giacconi et al. (2002), we have revised some optical/X-ray associations according to the improved astrometry provided by Alexander et al. (2003). Only sources with spectroscopic redshifts have been included in the CDF-N sample, because no details are given on the photo-$z$ quality in Burger et al. (2003). The larger CDF-S redshift completeness allows us to obtain a counting statistic per redshift bin similar to that of the CDF-N despite the shorter exposure.

Individual source spectra have been stacked together in seven redshift bins spanning the $z = 0.5–4$ range (Table 1). The choice of bin sizes and distribution is driven by a trade-off between the number of counts in each bin and the need to sample a corresponding observed energy range narrow enough to detect the spectral feature, keeping at the same time the instrumental response as uniform as possible. For these reasons, the redshift interval below $z = 0.5$ is not considered; moreover, the redshift interval $1.7 < z < 2.5$ is excluded because the iron line is redshifted in the ∼1.8–2.4 keV energy range, which encompasses the sharp drop in the effective area due to the instrumental iridium edge. The iron line signal is not expected to be significantly diluted by non-AGN sources. Below $z = 2$, the Kα line falls in the hard band (>2 keV), where the detected sources are mostly AGNs. At higher redshifts, it is shifted to the soft band, but then only sources with AGN luminosities can be detected. In order to avoid contamination by a few individual bright sources, which could dominate the stacked signal, we have excluded from each bin the brightest object, if its contribution exceeds 50% of the entire flux in the bin. The chosen redshift bins, the expected position of the 6.4 keV line, the bin width, and the number of sources in each bin are listed in Table 1. The final sample includes 171 sources in the CDF-N and 181 in the CDF-S, spanning the luminosity range $L_{1–6\text{ keV}} = 10^{41}$–$10^{45}$ erg s$^{-1}$ (see Table 1). The small solid angle (∼0.2 deg$^2$) covered by the deep fields does not allow us to sample the AGN population at higher luminosities.

2.2. X-Ray Stacking

The X-ray data for both the CDF-N and CDF-S observations have been retrieved from the public archive and processed with standard tools, making use of the calibrations associated with the CIAO$^1$ software (ver. 3.0). A total of 20 and 11 pointings in the CDF-N and CDF-S, respectively, were summed together with the merge_all$^2$ script in two different merged event files. The charge transfer inefficiency and gain$^3$ corrections were also applied to each single pointing.$^4$ Spectra, response matrices, and effective areas of the stacked spectrum in each redshift bin were extracted from the merged event files using the standard CIAO tools developed to properly weight responses and effective area files for multiple extraction regions (e.g., mkwarf, see Civano et al. 2005 for a detailed description of the procedure). The target positions in each redshift bin span almost all the off-axis angles; thus, the extraction radius was varied from 4′ to 16′, depending on the source brightness and off-axis position. Several background spectra were extracted with the same procedure from a stack of regions near each source in each redshift bin and varied in size and shape. Finally, the stacked spectra in each redshift bin of both the CDF-N and CDF-S were summed together with standard FTOOLS routines (mathpha, addarf, addrmf), weighted for both the exposure time and the number of counts. In the following, we consider only the resulting CDF-N+CDF-S spectra.

3. Spectral Analysis

Since we are interested in emission features over a well-defined energy range, source spectra have been extracted in the 1–6 keV band, to minimize calibration uncertainties in the low-energy response. X-ray spectra were rebinned to have at least 40 counts per keV bin and fitted with XSPEC (ver. 11.3.0; Arnaud 1996); errors are reported at the 90% confidence level for one significant excess above a power-law continuum is present over the energy range from 6.4 to 12 keV. With the exception of the highest redshift bin, a significant excess above a power-law continuum is present over the energy range from 6.4/(1 $+$ $z_{\max}$) to 6.4/(1 $+$ $z_{\min}$) keV.

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1 See http://cxc.harvard.edu/ciao.
2 See http://cxc.harvard.edu/ciao3/threads/merge_all.
3 See http://hea-www.harvard.edu/~alexey/acis/ogain.
4 We have also verified that by applying the new gain correction tool released with the CALDB 2.28 version the results are not modified.
5 See also http://asc.harvard.edu/cwc/proceedings/03_proc/presentations/zhao/s021.html.
where \( z_{\text{min}} \) and \( z_{\text{max}} \) are the bin boundaries (see Fig. 1). We then added a redshifted Gaussian component (model po + zgauess) with the width free to vary, centroid energy fixed at 6.4 keV, and redshift fixed at the mean value of each bin (\( \bar{z} \)), and verified that in all cases the fit improved, although with a different level of significance. Table 1 lists the best-fit parameters for each redshift bin. The equivalent widths (EWs) quoted in Table 1 are measured in the observed frame. To get the intrinsic, rest-frame EWs, a multiplicative factor \( 1 + \bar{z} \) must be applied.\(^6\)

### 3.1. Safety Checks

In order to check whether the results are dependent on the counting statistics and/or the energy range over which the continuum underlying the iron excess is measured, we have performed several safety checks.

First, we have further excluded in each bin the two or three brightest sources, if their contribution to the total counts was larger than 60\%. Then, spectral fits were repeated in the 2.2–6 keV energy range for sources at \( z < 2 \). Finally, a redshifted absorption component (assumed to be at \( \bar{z} \) in each redshift bin) was added to the continuum. In all cases, the spectral parameters were found to be in agreement, within the statistical errors, with those reported in Table 1. Furthermore, for the \( z < 2 \) bins for which the statistics is higher, we verified that, when the redshift of the line component is left free to vary, the resulting best-fit redshift is always almost coincident with that expected from a line at 6.4 keV.

Extensive simulations have also been performed to quantitatively assess the line broadening introduced by redshift smearing. The spectra of the sources contributing to each bin were modeled as a single power law plus a narrow unresolved (\( \sigma = 0.1 \) keV) Kα line. The actually observed source redshift distribution within the bin is further assumed, and the individual simulated spectra are stacked together. With the exception of the \( z = 0.9–1.1 \) bin, all the measured widths are in agreement with those resulting from the simulations and therefore consistent with being produced by the superposition of narrow features (but see also § 4).

According to XRB synthesis models, a large fraction of the sources contributing to each redshift bin are obscured by column densities in the range \( \sim 10^{22}–10^{24} \) cm\(^{-2} \). When obscured sources at different redshifts are stacked together, the iron line underlying continuum is expected to be modified, with respect to a single power law, by the most prominent absorption features, such as the low-energy cutoff and the 7.1 keV iron edge. To take this into account, we assumed a continuum shape as resulting from the Gilli et al. (2001) model once the AGN luminosity function is integrated in the narrow redshift bins adopted here. Although the recomputed EWs are lower than those reported in Table 1 (by about 30\%–50\%), the line excess is still significant. A more detailed investigation would require an extensive analysis of the AGN synthesis model’s parameter space and is beyond the purposes of this Letter.

### 4. Discussion

The rest-frame EWs for the seven redshift bins are compared (Fig. 2) with those predicted by the XRB synthesis model of Gilli et al. (2001; shaded area in Fig. 2). The line EW distribution is modeled following Gilli et al. (1999; see their Table 4) and is a function of the absorption column density, increasing from about 250 eV for unobscured sources to 400 eV for obscured (\( \log N/H_\odot < 24 \)) AGNs, reaching about 2 keV for Compton-thick sources. These values are constant over the entire redshift range. The upper bound of the shaded region has been computed assuming EW = 280 eV for unobscured sources, consistent with the average value measured by ASCA in the nearby universe. Recent XMM-Newton and Chandra results have questioned the presence of broad iron lines in many unobscured type 1 AGNs, measuring in turn a lower EW \( \sim 100–150 \) eV on average along with a decrease of the line EW toward high luminosities (e.g., Page et al. 2004). We have quantitatively estimated the effects of reducing the line EW among unobscured sources by considering the most conservative case of no iron emission at all (lower bound in Fig. 2). Since in our model most of the iron signal is produced by obscured sources with \( 22 < \log N/H_\odot < 24 \) cm\(^{-2} \), the overall EWs are reduced by only 15\%–20\%.

The lack of any dependence of the average line intensity on redshift up to \( z \sim 3 \) could be naively interpreted as a constant iron abundance with redshift. The real case is likely to be much more complicated, given the several factors affecting the detected signal. As an example, the population of heavily obscured Compton-thick sources (which have the strongest iron lines) might be hiding among

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\(^{6}\) The superposition of sources at different redshift in each bin should return a slightly different multiplicative factor, but the difference in the rest-frame EW obtained by using \( 1 + \bar{z} \) is negligible.
FIG. 2.—Rest-frame EWs as a function of redshift compared with the model predictions (shaded strip; see text for details). [See the electronic edition of the Journal for a color version of this figure.]

Our findings are also consistent with those reported by Strebyanska et al. (2005) from the analysis of the rest-frame stacked spectrum of identified sources in the XMM-Newton observation of the Lockman Hole (∼400 eV; when a Gaussian profile is considered). The residuals leftward of the iron line, which in our fits are more prominent in the bins with the highest number of sources and counting statistic (z = 0.5–0.7 and 0.9–1.1), suggest the presence of a broad redshifted component, similar to that observed by Strebyanska et al. (2005). Since the main goal of the present analysis is the detection of iron emission in the sources of the XRB up to high redshifts, our approach is not designed to investigate in detail the average line shape. We recall, however, that the observed EW and line profile are dependent on an accurate modeling of the underlying continuum. The superposition of absorbed spectra with different redshifts has the effect of reducing the measured EW (see §3) and furthermore may produce a spurious red wing.

5. SUMMARY

We report the detection of iron emission up to z ∼ 3 in the X-ray spectra of faint Chandra sources stacked into different redshift bins. The measured EWs are in agreement with a scenario in which the lines are intrinsically narrow and their intensity does not change significantly with redshift (and/or luminosity), which can be interpreted as a constant iron abundance as a function of redshift. Extensive simulations and safety checks have been performed in order to test the reliability of our results. Even taking into account the effects of absorption features, which modify the high-energy power law in obscured sources, the detection of the emission line remains significant. Despite their prominent iron lines, our approach does not allow us to put tight constraints on the number density of Compton-thick sources, which suffer from extreme absorption in the Chandra band and can be detected only in small numbers compared to Compton-thin AGNs. Although there might be hints for the presence of gravitationally redshifted broad-line components, we caution that their intensity and profile significantly depend on the modeling of the underlying continuum.

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