A broad iron Kα line at $z = 1.146$

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ABSTRACT

We report the discovery of a strong iron Kα line in the hard X–ray selected source CXOJ 123716.7+621733 in the Chandra Deep Field North survey at $z = 1.146$. The analysis is made possible by the very deep exposure $\sim 2$ Ms and low background of the ACIS detector. The line profile seems to be inconsistent with a narrow feature. The best fit solution is achieved with a broad line. Most of the flux in the broad component originates at energies below 6.4 keV with a shape similar to that expected from emission in the innermost regions of the accretion disk.

Key words: Galaxies: active – Galaxies: individual: CXOJ 123716.7+621733 – X-rays: galaxies

1 INTRODUCTION

The strongest emission feature in the hard X–ray spectrum of an active galactic nucleus (AGN) is the fluorescent FeKα emission line at 6.4–7 keV. Since its discovery by early X–ray observations, it is by now recognized to be an ubiquitous emission line at 6.4–7 keV. Since its discovery by early X–ray observations, it is by now recognized to be an ubiquitous emission line at 6.4–7 keV. Since its discovery by early X–ray observations, it is by now recognized to be an ubiquitous emission line at 6.4–7 keV. Since its discovery by early X–ray observations, it is by now recognized to be an ubiquitous emission line at 6.4–7 keV.
2 X-RAY DATA ANALYSIS

The X-ray data retrieved from the public archive have been processed with standard procedures making use of the calibrations associated with the CIAO software\(^1\) (version 2.3). Since the 20 separate ACIS–I observations that make the 2Ms CDF\(\text{N}\) have been performed at different roll angles and aim-points, the source position in detector coordinates changes during the whole observation. Since the CCD response depends on the position over the detector, source counts have been extracted from each of the 20 observations taking into account the dependence in size of the PSF with off-axis angle. The position of our target is always between 3 to 5 arcmin from the aim-point, thus the extraction radius was varied from 4 to 5 arcsec enclosing a constant fraction (90\%) of the PSF. Background regions were chosen locally for each single observation. The time dependent quantum efficiency degradation\(^2\) of the ACIS at low energies was also taken into account in the computation of ancillary response files for each dataset. Spectra, response matrices and effective areas, weighted by the number of counts in each observation, were summed using standard FTOOLS routines. There is no evidence of substantial flux variability. The background subtracted count rates in each of the 20 single observations never deviate from the average (\(\sim 1.4\) counts/ksec) by more than 20\% with the exception of three exposures where the variation is of the order of 50\%. The resulting effective exposure time of 1840 ks and the net source counts (2620 in the 0.6–7 keV band) are fully consistent with the values quoted in the 2Ms X-ray catalog (Alexander et al. 2003a). The slightly non–standard energy range considered for the spectral analysis is driven by the choice to keep the background level always below the 10\% of the total counts. The summed spectrum was then rebinned with at least 25 counts per bin. Spectral analysis was carried out with XSPEC (Version 11.2), errors are reported at the 90\% confidence level for one interesting parameter (\(\Delta \chi^2 = 2.71\)).

2.1 Spectral analysis

A single power law fit plus absorption (first line of Table 1) provides a good description of the broad band 0.6–7 keV continuum. The power law slope is rather flat (\(\Gamma \simeq 1.5\)) while the best fit column density (\(\sim 1.8 \times 10^{22} \text{ cm}^{-2}\) rest-frame) is clearly inconsistent with the Galactic column density towards the CDF–N (\(N_{\text{H,gal}} = 1.6 \times 10^{20} \text{ cm}^{-2}\)). The observed 2–10 keV flux of \(\sim 1.7 \times 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}\) corresponds to a rest frame luminosity of \(\sim 7.8 \times 10^{33} \text{ erg s}^{-1}\) which is typical of a bright Seyfert 1 galaxy. The broad band 0.5–10 keV unabsorbed luminosity is \(\sim 1.2 \times 10^{44} \text{ erg s}^{-1}\).

Significant residuals around 3 keV are clearly evident (Fig. 1), strongly indicating the presence of a line–like feature.

We therefore added a Gaussian line with rest frame energy fixed at 6.4 keV. Leaving both the line width and redshift free to vary the fit quality is significantly improved (at more than 99.99999\% level according to the F–test) and statistically acceptable (second line in Table 1). The line width is broader than the instrument resolution. Moreover, the best fit energy centroid is significantly higher than that expected on the basis of the spectroscopically measured redshift (see Fig. 2). The discrepancy would be even higher if a ionised line at 6.7 or 6.96 keV is considered.

Given that the redshift obtained from optical spectroscopic observations is unlikely to be affected by such a large error, we have fixed the centroid of the neutral line at \(z = 1.146\) and repeated the fitting procedure. Leaving the line width free to vary, the quality of the fit is marginally worse than in the previous case (third line in Table 1). From a visual inspection of the spectrum it appears evident that most of the line width has to be ascribed to a red tail with respect to the redshifted centroid of 6.4 keV. This effect is clearly seen in Figure 3 where the line width is fixed at the instrumental energy resolution.

2.2 Safety checks

Although the statistical significance regarding the presence of a line feature at 2.9 keV is very robust, as indicated by the

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The overall properties of the line profile are, at least qualitatively, similar to those of an emission line originating in the innermost region of an accretion disc. We next fitted the data with the Schwarzschild disk line model of Fabian et al. (1989). It is well known that disk models have a considerable parameter degeneracy and thus the interpretation of the results obtained by standard fitting procedures is not straightforward. Given that the quality of our data is not such to allow a detailed parameter investigation, the best fit solutions and associated error bars have to be treated with caution.

In all the fits we have assumed a neutral iron Kα line at 6.4 keV rest frame. First of all we have considered a model where only the inner disc radius is fixed at the last stable orbit of a non-rotating black hole (6R_s). The quality of the fit is statistically acceptable (χ^2/d.o.f.:=94/106) and the improvement with respect to a single power law is significant at more than 99.999% level according to an F-test. The formal best fit solution returns a power law index for the disk emissivity (which scales as R^{-q}) q ~ 2.5 and an inclination angle of 7 degree, while the outer disc radius (R_{out}) is basically unconstrained towards high values. The line equivalent width (EW) in the observed frame is ~ 425 ± 125 eV, corresponding to ~ 910 ± 270 eV in the rest-frame. The 1–5 keV X-ray spectrum deconvolved by the instrument response is reported in Figure 4. Assuming a rather optimistic criterion of Δχ^2=4.6 (corresponding to 90% interval for two parameters) we have tried to estimate errors for both R_{out} and q, which, as expected are only poorly constrained: R_{out} > 35R_s, q < 3.5.

For a disk centrally illuminated by a point X-ray source situated at a height H above the disk center, q is expected to lie in the range 0–3 (Fabian et al. 1989) depending on the considered disc radius. Most of the line flux originates from radii of the order of H where the emissivity index is q ~ 2 (Laor 1991). Assuming such a value for the disc emissivity law, it is possible to better constrain the outer disc radius and inclination angle (Fig. 5). As far as the disc inclination angle is concerned, we note that it is always lower than ~ 30°.
been clearly detected in the X–ray spectrum of the relatively bright, hard X–ray source CXOJ 123716.7+621733 at \( z = 1.146 \) in the Chandra Deep Field North. The broad band \( 0.6–7 \) keV Chandra spectrum is best described by a relatively hard (\( \Gamma \simeq 1.5 \)) power law plus significant intrinsic absorption \( N_H \sim 1.8 \times 10^{22} \text{ cm}^{-2} \). An almost equally good fit is obtained if the continuum emission is parameterized with a steeper (\( \Gamma = 1.8 \)) slope plus a reflection component as commonly observed in nearby Seyfert galaxies.

The line profile is not consistent with a narrow feature, being significantly broader than the ACIS–I CCD resolution at that energy. Such a result does not depend on the adopted shape of the underlying continuum.

In order to reproduce both the observed width and the optical spectroscopic redshift, most of the line flux has to originate in a red wing. An adequate description of the overall line shape has been obtained with a relativistic line model. Although the quality of the data is not such to break the degeneracy between the various line parameters, the present observation suggests an almost face–on orientation of the accretion disk.

The line equivalent width \( (860 \pm 260 \text{ eV}) \) is larger than the average values measured by ASCA for a sample of nearby bright Seyfert galaxies. Nandra et al (1997b) report an average value of \( 230 \pm 60 \text{ eV} \), for a relativistic line model. Plausible possibilities include iron overabundance as in MCG–6–30–15 (see e.g. Lee et al. 1999) and/or an enhanced contribution of the reflected flux possibly associated to time variability. The latter possibility appears unlikely given the lack of significant flux variability over more than two years. It must be noted that large values of the EW are not unusual among relatively faint X–ray sources (George et al. 2000) and likely to be due to a selection effect associated to the uncertainties in modelling the continuum and line spectrum.

The broad band properties of CXOJ 123716.7+621733 (namely, the high X–ray to optical ratio, \( (\log f_X/f_\text{opt} \simeq 1) \), the X–ray column density \( (> 10^{22} \text{ cm}^{-2}) \) and the optical, near–infrared colors \( (B – V = 0.7, R – K = 4.4; \text{Barger et al. 2003}) \) indicate substantial obscuration of the nuclear source. There is also no evidence of typical AGN emission lines in the low resolution optical spectrum (Barger et al. 2002).

The present results indicate that the iron K\( \alpha \) line could be the strongest AGN signature in the broad band spectra (from optical to X–rays) of distant, obscured AGN for which only a low signal–to–noise optical spectrum covering a relatively small range of wavelengths is available, and highlight the uniqueness of X–ray observations in the study of supermassive black holes at cosmologically interesting distances.

The study of relativistically broadened iron line profiles would greatly benefit from deep X–ray observations with the XMM–Newton large collecting area telescopes. Observations with the new generation of X–ray observatories (Constellation X and XEUS) will allow systematic studies of iron line properties at high redshifts.

3 DISCUSSION AND CONCLUSIONS

A strong emission feature due to the K\( \alpha \) iron line has been clearly detected in the X–ray spectrum of the relatively
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REFERENCES

Alexander D.M. et al., 2003a, AJ, 126, 539
Alexander D.M. et al., 2003b, AJ, 125, 383
Barger A.J. et al., 2002, AJ, 124, 1839
Barger A.J. et al., 2003, AJ, 126, 632
Dewangan G.C., Griffiths R.E., Schurch N.J., 2003, ApJ, 592, 52
Fabian A.C., Rees M.J., Stella L., White N.E., 1989, MNRAS, 238, 729
Fabian A.C., Iwasawa K., Reynolds C.S., Young A.J., 2000, PASP, 112, 1145
Fabian A.C. et al., 2002, MNRAS, 335, L1
Gandhi P., Crawford C.S., Fabian A.C., Johnstone R.M., 2004, MNRAS, 348, 529
George I.M. et al., 2000, ApJ, 531, 52
Iwasawa K., Taniguchi Y., 1993, ApJ, 370, L61
Laor A., 1991, ApJ, 376, 90
Lee J.C., Fabian A.C., Brandt W.N., Reynolds C.S., Iwasawa K., 1999, MNRAS, 310, 973
Nandra K., George I.M., Mushotzky R.F., Turner T.J., Yaqoob T., 1997a, ApJ, 488, L91
Nandra K., George I.M., Mushotzky R.F., Turner T.J., Yaqoob T., 1997b, ApJ, 477, 602
Norman C. et al., 2002, ApJ, 571, 218
Page K.L., O’Brien P.T., Reeves J.N., Turner M.J.L., 2004, MNRAS, 347, 316
Reeves J.N., Turner M.J.L., 2000, MNRAS, 316, 234
Reeves J.N. et al., 2001, A&A, 365, L116
Reynolds C.S., Nowak M.A., 2003, Physics Reports, 377, 389
Richards E.A., 2000, ApJ, 533, 611
Tanaka Y. et al., 1995, Nature, 375, 659
Turner T.J. et al., 2002, ApJ, 574, L123
Vignali C., Comastri A., Cappi M., Palumbo G.G.C., Matsuoka M., Kubo H., 1999, ApJ, 516, 582