Relativistic Iron lines at high redshifts

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Summary. The shape and the intensity of the 6.4 keV iron line bring unique information on the geometrical and physical properties of the supermassive black hole and the surrounding accreting gas at the very center of Active Galactic Nuclei. While there are convincing evidences of a relativistically broadened iron line in a few nearby bright objects, their properties at larger distances are basically unknown. We have searched for the presence of iron line by fully exploiting \textit{Chandra} observations in the deep fields. The line is clearly detected in the average spectra of about 250 sources stacked in several redshift bins over the range \(z=0.5\text{--}4.0\). We discuss their average properties with particular emphasis on the presence and intensity of a broad component.

1 Introduction

Most of the accretion power, which makes Active Galactic Nuclei luminous hard X-ray sources, is released in the innermost regions around the central Supermassive Black Hole (SMBH), where the relativistic effects in the strong field limit (gravitational redshift and light bending) significantly affect the emerging spectrum. In particular the iron emission line at 6–7 keV is by far the most significant feature in the AGN X-ray spectra and a detailed study of its profile provides unique information about the gas properties and the nature of the spacetime in the proximity of the SMBH (see [1] for an exhaustive review including the most recent observational results).

A key issue concerns the shape of the line profile and in particular of the red wing, which is much broader if the emitting gas is accreting over a rapidly spinning SMBH. If this is the case, the innermost stable orbit is much closer (\(\approx 1.24r_g\) where \(r_g = GM/c^2\)) to the central BH than for a non rotating BH (\(\approx 6r_g\)) and the emitted photons suffer from stronger general relativistic effects which are in principle visible in the line profile provided that enough sensitivity is reached in the 2–10 keV band.

The profile of the broad emission line in the nearby Seyfert galaxy MCG–6–30–15 represents a textbook case. The presence of a relativistic line with a skewed profile extending down to 4 keV (and during some episodes even at lower energies [2]), was first unambiguously determined by ASCA [3], and then confirmed by essentially all the X-ray experiments (i.e. BeppoSAX, XMM–\textit{Newton} and \textit{Chandra}). While the evidence for a line profile distorted
by general relativistic effects is quite solid in MCG–6–30–15, and tested against alternative solutions such as complex absorption [4], the observational constraints on other nearby Seyfert galaxies are not such to rule out alternative possibilities. Moreover the search for broad iron lines beyond the nearby Universe is strongly hampered by the sensitivity of the present instruments and only a few tentative positive results were reported [5, 6].

Deep XMM–*Newton* and *Chandra* observations offer the possibility to search for iron line emission at much larger distances (z >0.5) at least in a statistical sense, by stacking the X–ray counts of a large number of X–ray sources.

2 Stacking in XMM–*Newton* and *Chandra* deep fields

The individual spectra of 53 Type 1 AGN and 43 Type 2 AGN in the deep XMM–*Newton* pointing (∼800 ksec) of the Lockman Hole for which a spectroscopic redshift is available, were brought to rest–frame and then summed together [7]. The residuals of a single power law fit to the stacked spectra clearly show a prominent iron line at 6.4 keV with a skewed profile extending towards lower energies. A good fit to both (type 1 and type 2) line profiles is obtained with a disc model with an innermost orbit around ∼3 rg, suggesting that, on average, most of the SMBH in distant AGN are spinning. The above described approach maximizes the counting statistic in the energy band covered by the line, but at the same time looses, by definition, any information about the redshift dependence of line properties.

A complementary approach [8] has been pursued by stacking the X–ray counts, in the observed frame, of spectroscopically identified sources in the *Chandra* deep fields (CDFN & CDFS) in seven redshift slices spanning the z=0.5–4 range. 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 an observed energy range narrow enough to detect the spectral feature, keeping at the same time the instrumental response as uniform as possible. The sample includes 171 sources in the CDFN and 181 in the CDFS, spanning the luminosity range \( L_{2–10\text{keV}} = 10^{41} – 10^{45} \text{ergs s}^{-1} \). With the exception of the highest redshift bin, a significant excess above a power–law continuum is present at the expected energy (see Fig. 1).

The residuals leftward of the iron line (which are more prominent in the bins with the highest number of sources and counting statistics z=0.5–0.7 and 0.9–1.1) suggest the presence of a broad redshifted component, similar to that observed by XMM [7].
Fig. 1. Residuals of a simple power-law fit to the source spectra in seven different redshift bins as labeled. The vertical line in each panel is at the expected position for the redshifted 6.4 keV Fe Kα line while the shaded region encompasses the bin width reported in Table 1 and defined as $\Delta E = 6.4/(1+z_{\text{max}}) - 6.4/(1+z_{\text{min}})$ keV.
Fig. 2. Left panel: The residuals of a single power law fit to the stacked spectra of the 37 X-ray sources in the CDFS redshift slice $0.664 < z < 0.742$. The vertical lines correspond to the expected position of the 6.4 keV line at the two extremes of the interval. Right panel: The fit and residuals of a single power law fit to the stacked spectra of the 12 objects in the CDFN redshift slice $1.14 < z < 1.18$. The expected position of the redshifted 6.4 keV line is coincident with the peak in the residuals at $\sim 2.96$ keV.

3 Searching for broad lines in deep fields

The stacking results described above, motivated by two different key scientific objectives, were obtained following two different approaches in the stacking procedure. The XMM–Newton stacked spectra were obtained by unfolding the instrumental response with a power law model. In this way it is possible to shift and add the individual spectra and maximize the S/N ratio around the iron line energy. The drawback is a model dependent parameterization of the underlying continuum. The alternative strategy [8], following a more conventional approach, does not suffer of the model dependent unfolding of the instrumental response, but at the same time it is not well suited for a study of the line profile which is smeared in each redshift bin by the bin size itself. A third possibility which combines the pros of the two above mentioned methods would be to stack a large number of source spectra within a redshift range which is small enough that the energy (redshift) spread is negligible or at least smaller than the instrumental energy resolution.

The presence of significant spikes in the redshift distribution observed in both CDFS [9] and CDFN [10] has prompted us to further investigate such a possibility. The residuals of a single power law fit to the stacked spectra of the 37 X-ray sources in the CDFS redshift slice ($0.664 < z < 0.742$) and the 12 objects in the CDFN redshift slice ($1.14 < z < 1.18$) are shown in Fig. 2. In both cases, a broad wing is clearly visible redward of a narrow core corresponding to the redshifted energy of the 6.4 keV line. In both samples the line shape is well fitted by a relativistic disk line model. However, the accuracy in the determination of the inner disk radius is not good enough to constrain the SMBH spin (Fig. 3). While this is not surprising given the
available counting statistics, the similarity of the very shape of the observed profile to what expected by a relativistic line is tantalizing. Although the perspectives of the detection of spinning BH at high redshift are promising a few words of caution appear to be appropriate. It is well known that the line intensity and especially the line profile are dependent on an accurate modeling of the underlying continuum and in particular are sensitive to the presence of complex absorption [1]. The latter possibility is especially relevant for the analysis of the stacked spectrum of the deep field sources which are mostly obscured AGN. The 2–7 keV continuum resulting from the superposition of absorbed spectra with different redshifts is modified with respect to a single power law, by the absorption cut–off and most important by the 7.1 keV iron edge. The net effect of the latter can be approximated with a smeared edge which effectively enhance the X–ray continuum just below the iron line emission. The residuals of a single power law fit to the sources in the z=0.5–0.7 bin suggest the presence of an extended broad wing. (Fig. 4, left panel) which is almost completely accounted for by the continuum predicted by X–ray background synthesis models [11] in the same redshift bin (Fig. 4, right panel).

4 Conclusions

The detection of spinning BH at high redshift is probably close to the capabilities of present instrumentation provided that deeper observations and/or larger samples of sources are collected and appropriately analyzed especially for what concern the modelling of the underlying continuum. Future missions with large collecting area will surely provide a step forward in such a direction.
Fig. 4. **Left panel:** The residuals of a single power law fit to the $z=0.5–0.7$ bin adapted from [8]. **Right panel:** The unfolded spectrum of a complex absorption model fit plus a narrow gaussian emission line at 6.4 keV (rest–frame) to the same data set.

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