The iron Kα Compton Shoulder in transmitted and reflected spectra

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ABSTRACT

We calculate the Equivalent Width of the Core and the centroid energy and relative flux of the 1st order Compton Shoulder of the iron Kα emission line from neutral matter. The calculations are performed with Monte Carlo simulations. We explore a large range of column densities for both transmitted and reflected spectra, and study the dependence on the iron abundance. The Compton Shoulder is now becoming observable in many objects thanks to the improved sensitivity and/or energy resolution of XMM–Newton and Chandra satellites, and the present work aims to provide a tool to derive informations on the geometry and element abundances of the line emitting matter from Compton Shoulder measurements.

Key words: Line: formation – galaxies: active – X-rays: galaxies

1 INTRODUCTION

Iron Kα fluorescent lines emitted in neutral matter consists (in the matter rest frame) of a narrow core (corresponding to the line photons emerging unscattered from the emitting region) and several Compton Shoulders (CS; see Matt et al. 1991; George & Fabian 1991; Leahy & Creighton 1993; Sunyaev & Churazov 1996), corresponding to line photons emerging after one or more scatterings. While the higher order CS are expected to be very faint, the first order CS (hereinafter CS1) should now be observable in many objects thanks to the improved energy resolution and sensitivity of the instruments onboard Chandra and XMM–Newton (see Kaspi et al. 2002; Bianchi et al. 2002; see also Iwasawa et al. 1997 for the only pre-Chandra observation of a Compton Shoulder).

In this paper we calculate, by means of Monte Carlo simulations, the relative amount and centroid energy of CS1, as well as the Equivalent Width (EW) of the unscattered line photons (Narrow Core, hereinafter NC), in both transmitted and reflected spectra. In the former case, we adopt a spherical geometry, and explore a large interval of the column density. For the latter case we assume a plane–parallel geometry and calculate CS1 properties as a function of the inclination angle for different values of the column density in the perpendicular direction. The dependence of line properties on the iron abundance is also explored.

2 CALCULATIONS

The simulation code employed here is described in Matt et al. (1991; 1997), and we defer the reader to these papers for details. To avoid contamination from Compton scattered continuum photons, we injected only primary photons with energies larger than the iron Kα edge.

For each simulated spectrum, we calculated three quantities: a) the EW of the NC with respect to the primary (unabsorbed) emission; b) the Centroid Energy ($E_c$) of CS1, defined as:

$$E_c = \frac{\int_{E_{\text{rec}}}^{6.4} EN(E)\,dE}{\int_{E_{\text{rec}}}^{6.4} N(E)\,dE}$$

where $E_{\text{rec}}=6.2436$ keV is the minimum energy of a line photon after one scattering, $N(E)$ is the number of line photons per unit energy at a given energy, and the integral does not of course include the NC; c) the ratio $f$ between the total number of photons in the CS1 ($= \int_{E_{\text{rec}}}^{6.4} N(E)\,dE$) to that in the NC. It should be noted that with these definitions, the CS1 may actually include also line photons scattered twice or more times, provided that the energy loss per scattering is small enough (i.e. small scattering angles) that the emerging photon has an energy still larger than $E_{\text{rec}}$. However, the chosen definitions are the most useful when comparing the calculations with real data.

Element abundances and photoabsorption cross sections are those given by Morrison & McCammon (1983) (the iron abundance in number is $3.3 \times 10^{-5}$; a value about 40 percent higher is given by Anders & Grevesse 1989). A
larger (smaller) iron abundance results in an increase (decrease) of the EW of the iron line (see Matt et al. 1997 for a detailed discussion), and in a decrease (increase) of $f$ due to the larger (smaller) ratio of photoelectric absorption to Compton scattering. To quantify these effects, we have run the Montecarlo code (in the optically thick case only for reflected spectra) also for $A_{Fe}=0.5$ and 2, where $A_{Fe}$ is the iron abundance in units of the cosmic value.

The primary spectrum has been assumed to be a power law with photon spectral index 2. Different indices will result on somewhat different values of the EW of the NC (see George & Fabian 1991). $E_f$ and $f$ are instead independent of the spectral index, at least in the optically thin case (in the optically thick case there should be a small dependence on the slope due to the energy dependence of photoabsorption, and therefore of the depth at which the interaction occurs.)

Finally, it must be remarked that we assumed cold electrons, i.e. we neglected both thermal motions for free electrons and their motion in the atoms and molecules, if they are bound. In real situations, where these effects are considered, the minimum energy after one scattering, $E_{min}$, may be lower than the value given above. The adopted approximation will also lead to an artificially sharp backscattering peak in the spectrum of Figs. 2 and 5 below, and this should be considered when fitting real data. (For a complete discussion of these effects, see Sunyaev & Churazov, 1996.) We note that electron temperatures are expected to be large in the inner regions of accretion discs, especially in Galactic Black Hole candidates, but then relativistic distortion are expected to be even larger. Electron temperatures are instead expected to be low in e.g. circumnuclear matter in AGN; in these cases, effects due to the motion of bound electrons should instead be considered (see e.g. Fig. 4a of Sunyaev & Churazov 1996).

3 RESULTS

3.1 CS1 in transmitted spectra

We first calculated the line spectra when the cold matter lies along the line of sight (transmitted spectra). We explored a wide range of column densities, from $10^{22}$ to $5 \times 10^{24} \text{ cm}^{-2}$. We assumed a spherical distribution of the matter, with the source of the primary photons located at the centre of the sphere. The density of the matter is assumed to be constant.

We explored the case of spherical distribution of matter for three different values of the iron abundance $A_{Fe}$ with respect to the cosmic value (as for Morrison & McCammon 1983): 0.5 (Fig. 1, dotted lines), 1 (solid lines), 2 (dashed lines). The EW of the NC increases with the column density up to about $4 \times 10^{23} \text{ cm}^{-2}$, in agreement with previous calculations (e.g. Inoue 1989), and then decreases. The dependence on the iron abundance is linear in the $\tau_C \ll 1$ limit ($\tau_C = N_H/1.5 \times 10^{24} \text{ cm}^{-2}$), and less than linear when opacity effects become important (see Matt et al. 1997). The CS1 centroid energy and $f$ increase up to a Compton depth of about unity. The following decrease is due to the increasing importance of repeated scatterings. The dependence of both parameters on $A_{Fe}$ is not dramatic and, for $f$, almost negligible up to $\tau_C \sim 1$.

In Fig. 1 the spectrum of the CS1 is shown for three different column densities ($A_{Fe}$=1).

![Figure 1](image)

**Figure 1.** The EW of the NC (calculated with respect to the primary unabsorbed emission), centroid energy of CS1 and $f$ for a centrally illuminated spherical distribution of cold matter. The dotted, solid and dashed lines refer to $A_{Fe}$=0.5, 1 and 2, respectively.

3.2 CS1 in reflected spectra

We then calculated the CS1 properties for an isotropically illuminated plane–parallel slab. The EW of the NC (with respect to the primary emission only), the centroid energy of CS1 and $f$ are shown in Fig. 2 (solid lines) as a function of $\mu$, the cosine of the slab’s inclination angle. We firstly assumed optically thick matter (vertical column density of $2 \times 10^{25} \text{ cm}^{-2}$) and cosmic abundances. The EW of the NC increases with $\mu$ (as well known, see Matt et al. 1991; George & Fabian 1991), as does $f$, $E_{cent}$ instead, decreases with $\mu$.

Is is worth noting that in reflected spectra $f$, for the same iron abundance, is lower than in transmitted spectra, provided that the column density of the line–of–sight matter is larger than a few $\times 10^{23} \text{ cm}^{-2}$. This is because the average optical depth, with respect to the emerging surface, at which the first interaction occurs is lower in the former than in the latter case due to the isotropic illumination.

We then explored the dependence of the line properties on the iron abundance. In Fig. 3 the results for $A_{Fe}$=0.5 and 2 are shown (dotted and dashed lines, respectively). As expected, the EW is larger and $f$ smaller for the larger iron abundance, while the opposite occurs for the smaller iron abundance.

Finally, we calculated the line properties as a function of the vertical column density (Fig. 4). While the centroid energy is not significantly dependent on $N_H$, both $f$ and the EW of the core increases, as expected, with $N_H$ in the optically thin regime, to saturate for $N_H \sim 5 \times 10^{23} \text{ cm}^{-2}$. In
Figure 2. The spectrum of CS1 (in the cold electrons approximation, see text) in the transmitted case for column densities of $5 \times 10^{22}$ (solid line), $5 \times 10^{23}$ (dotted line) and $5 \times 10^{24}$ cm$^{-2}$ (dashed line). $A_{Fe}=1$.

Figure 3. The EW of the NC, centroid energy of CS1 and $f$ for an isotropically illuminated, optically thick ($N_H = 2 \times 10^{25}$ cm$^{-2}$) plane–parallel slab, as a function of $\mu$, the cosine of the inclination angle. The dotted, solid and dashed lines refer to $A_{Fe}=0.5$, 1 and 2, respectively.

the Compton–thin regime, moreover, these parameters are much less dependent on $\mu$ than in the optically thick case. It is worth noting that in the optically thin regime the values of EW and $f$ are larger than in transmitted spectra, for the same $N_H$, largely due to the different illumination (which is always normal to the surface in the spherical geometry, but not in the isotropically illuminated slab; in the latter case the effective column density becomes very large for grazing angles).

In Fig. 3 the spectrum of CS1 is shown for two different values of $\mu$ ($A_{Fe}=1$).

4 CONCLUSIONS

We have calculated the properties of the iron Kα Narrow Cores and of the first scattering Compton Shoulder in both transmitted and reflected spectra, refining and expanding previous works on the same subject (Matt et al. 1991; George & Fabian 1991; Leahy et al. 1993; Iwasawa et al. 1997; see Sunyaev & Churazov 1996 for a very detailed physical description of the process). The intensity of the Compton Shoulder is at most 30–40% of the Narrow Core of the line, with a centroid energy typically of about 6.3 keV or more.

Prior to the launch of Chandra, the Compton Shoulder was observed only in the ASCA spectrum of NGC 1068 (Iwasawa et al. 1997), with properties consistent with an origin in the Compton–thick torus of this source. Recently, thanks to the gratings onboard Chandra, two more cases have been reported. Bianchi et al. (2002) found a Compton shoulder in the HETG spectrum of the Circinus Galaxy. The value of $f$, i.e. about 20%, is consistent with reflection from the inner wall of the $4 \times 10^{24}$ cm$^{-2}$ torus.

Kaspi et al. (2002) measured a Compton shoulder in their 900 ks Chandra/HETG observation of the Seyfert 1 galaxy NGC 3783. The flux in CS1 is 14±4 percent of the narrow core, which in turn has an EW of 90±11 eV. The line is clearly due to reflecting matter, as no evidence for strong cold absorption is apparent. Looking at the values of $f$ in Figs. 3 and 4, it is possible to conclude that the reflecting matter should have a column density of at least $\sim 10^{23}$ cm$^{-2}$ (slightly lower values are allowed only if the iron is overabundant). The value of the EW is less directly usable, as the geometry of the reflector is unknown (the values in this paper refer to a $2\pi$ solid angle of the matter, subtended to an isotropic primary source). However, as it seems unlikely that the solid angle is much larger than $2\pi$, low values of the iron abundance are disfavoured.

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Figure 4. The EW of the NC, centroid energy of CS1 and $f$ for an isotropically illuminated, plane–parallel slab with vertical column density of $5 \times 10^{22}$ (dot–dashed lines), $10^{23}$ (long–dashed lines), $5 \times 10^{23}$ (short–dashed lines), $10^{24}$ (dotted lines) and $5 \times 10^{24}$ (solid lines) cm$^{-2}$. $A_{Fe}=1$.

Figure 5. The spectrum of CS1 (in the cold electrons approximation, see text) in the reflection case for $\mu=0.15$ (solid line) and $\mu=0.95$ (dotted line). $A_{Fe}=1$.

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