Chandra Detection of the Iron Compton Shoulder in the Circinus Galaxy

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We report on the detection of the iron Kα Compton shoulder with a flux of about 20 % the line core in the *Chandra* HEG spectrum of the Circinus Galaxy. This feature is predicted on theoretical grounds as arising from Compton scattering of the fluorescent line photons in optically thick matter, and the observed flux and width are fully consistent with Monte Carlo simulations, which are also presented here.

1. Introduction

Iron Kα fluorescent lines emitted in neutral matter consists (in the matter rest frame) of a narrow core (corresponding to line photons emerging unscattered from the emitting region) and several Compton Shoulders (CS) [1–4], 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* . Indeed, it was observed in the *ASCA* spectrum of NGC 1068 [6], the only pre-*Chandra* observation of a CS1, and in the *Chandra* HEG spectrum of NGC 3783 [5].

We present here results on the CS1 from Monte Carlo simulations [7] and report on the detection of the CS1 in the *Chandra* HEG spectrum of the Circinus Galaxy [8].

2. Calculations

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. For the latter case, the only one which will be presented here (see [7] for a complete report of all the results), 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.

The simulation code employed here is described in [1,9], 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:

$$E_c = \frac{\int_{E_{\rm rec}}^{6.4} EN(E)dE}{\int_{E_{\rm rec}}^{6.4} N(E)dE} \qquad (1)$$

where $E_{\rm rec}$=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 ($= \int_{E_{\rm rec}}^{6.4} N(E)dE$) 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 $E_{\rm rec}$. 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 [10] (the iron abundance in number is 3.3×10^{-5}; a value about 40 % higher is given by [11]). A larger (smaller) iron abundance results in an increase (decrease) of the EW of the iron line (see [9] 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 Monte Carlo code 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 in somewhat different values of the EW of the NC [2]. E_c 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, $E_{\rm rec}$, may be lower than the value given above. The adopted approximation will also lead to an artificially sharp backscattering peak in the spectrum of Fig. 3 below, and this should be considered when fitting real data. (For a complete discussion of these effects, see [4].) 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 [4]).

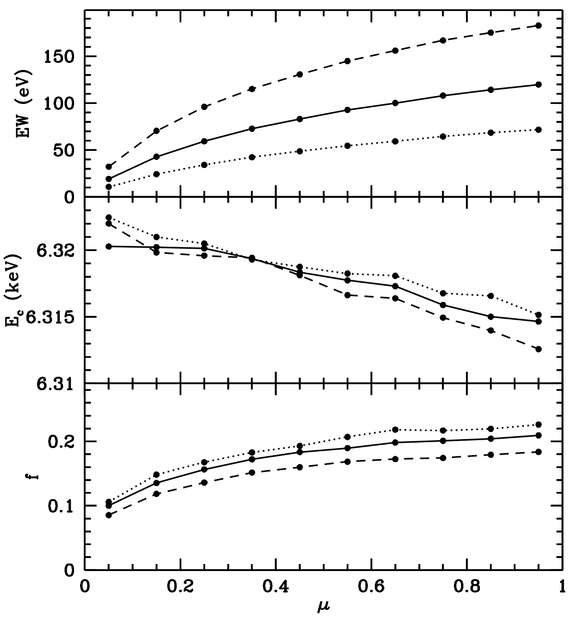

Figure 1. The EW of the NC, centroid energy of CS1 and f for an isotropically illuminated, optically thick ($N_H = 2\times10^{25}$ cm^{-2}) plane–parallel slab, as a function of μ, the cosine of the inclination angle. The dotted, solid and dashed lines refer to A_{Fe}=0.5, 1 and 2, respectively.

3. Theoretical results

We present here only the results 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. 1 (solid lines) as a function of μ, the cosine of the slab's inclination angle. We firstly assumed optically thick matter (vertical column density of 2×10^{25} cm^{-2}) and cosmic abundances. The EW of the NC increases with μ (as well known, see [1,2]), as does f. E_c, instead, decreases with μ.

We then explored the dependence of the line properties on the iron abundance. In Fig. 1 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. 2). 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 $N_H \sim 5\times10^{23}$ cm^{-2}. In the Compton–thin regime, moreover, these parameters are much less dependent on μ than in the optically thick case.

In Fig. 3 the spectrum of CS1 is shown for two

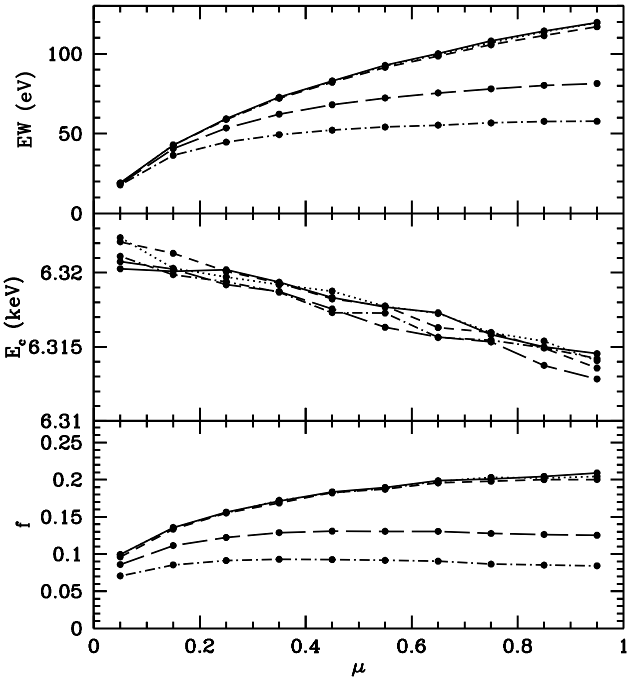

Figure 2. The EW of the NC, centroid energy of CS1 and f for an isotropically illuminated, plane–parallel slab with vertical column density of 5×10^{22} (dot–dashed lines), 10^{23} (long–dashed lines), 5×10^{23} (short–dashed lines), 10^{24} (dotted lines) and 5×10^{24} (solid lines) cm^{-2}. A_{Fe}=1.

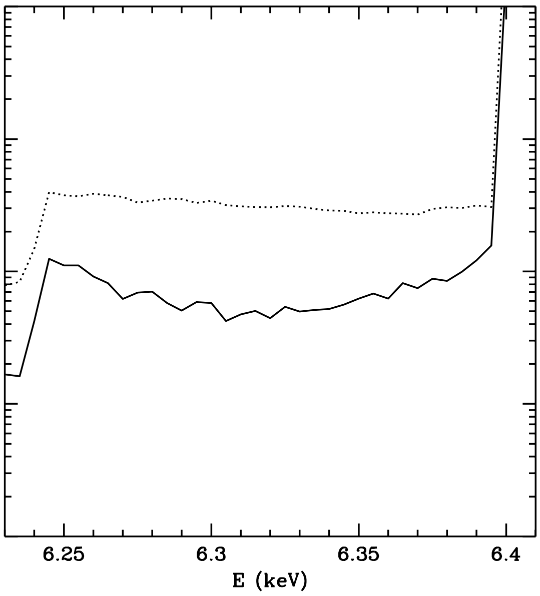

Figure 3. The spectrum of CS1 (in the cold electrons approximation, see text) in the reflection case for μ=0.15 (solid line) and μ=0.95 (dotted line). A_{Fe}=1.

different values of μ (A_{Fe}=1).

4. Data analysis

We re-analysed the HEG spectrum of the nucleus to look for the CS1 in the iron Kα line, which is not reported in Sambruna et al. (2001) [12], possibly because the response matrix included with the version of CIAO available at that time was less accurate than the new one.

Indeed, residuals in excess of the red wing of the 6.4 keV iron line are clearly visible in the data, if we use a power law description of the continuum between 5 and 8 keV and put three gaussian lines at 6.40, 6.67 and 7.04 keV, as required by the data (Fig. 4). We tried to fit this feature with the BOX1D function in *Sherpa*, which has a constant value in a given energy range and is identically null outside. This is a reasonable approximation of the theoretical profile (see Fig. 3). The best fit boundaries for the box are 6.15 keV and 6.40 keV, while the flux is $6.2 \pm 2.0 \times 10^{-5}$ ph cm^{-2} s^{-1}, that is $25 \pm 8\%$ that of the iron Kα line. If we keep the box boundaries fixed to the values expected from theoretical models (see below), the flux of the Compton shoulder is $5.1 \pm 1.8 \times 10^{-5}$ ph cm^{-2} s^{-1}, that is $20 \pm 7\%$ that of the iron Kα line core.

These values are fully consistent with the theoretical expectations. If it originated by reflection from a Compton-thick material ($N_{\rm H} > 10^{24}$ cm^{-2}), the first order Compton shoulder is expected to extend from 6.2436 keV to the core of the iron line, with a centroid at 6.31-6.32 keV and a flux of $15 - 20\%$ that of the core (Fig. 1).

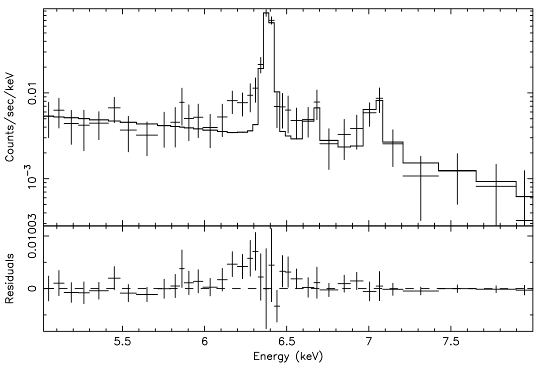

Figure 4. The Compton shoulder in the *Chandra* HEG spectrum showed as residuals from the best fit including three gaussian lines.

As a further test, we also fitted the Compton shoulder with XSPEC, adopting a simple gaussian line. We obtain a good correction of the residuals, with a centroid at $E_0 = 6.27$ keV and a FWHM $\sigma = 0.07$ keV. The flux of the Compton shoulder modelled in this way ($5.8^{+2.3}_{-2.6} \times 10^{-5}$ ph cm^{-2} s^{-1}) is fully compatible with that measured with *Sherpa*.

5. Conclusions

We presented here results on the iron Compton Shoulder from Monte Carlo simulations in the case of reflection from an isotropically illuminated plane-parallel slab. We then reported on the detection of such a feature on the HEG spectrum of the Circinus Galaxy. The observed flux and width are fully consistent with the theoretical expectations.

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