Acta Polytechnica **54**(3):177–182, 2014
doi:10.14311/AP.2014.54.0177

X-RAY TRANSMISSION AND REFLECTION THROUGH A COMPTON-THICK MEDIUM VIA MONTE-CARLO SIMULATIONS

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Abstract. The spectral shape of an X-ray source strongly depends on the amount and distribution of the surrounding material. The spectrum of a primary source which is located in an optically thin medium with respect to Compton scattering is mainly modified by photo absorption in the lower energy range and is almost unaltered above $\sim 10\,\mathrm{keV}$. This picture changes when the source is obscured by gas exceeding hydrogen column densities of $\sim 10^{24}\,\mathrm{cm}^{-2}$. At this degree of absorption it is likely that photons are scattered at least twice before leaving the medium. The multiple scatterings lead to a lack of photons in the high energy range of the resulting spectrum as well as to an accumulation of photons at moderate energies forming the so-called Compton-bump. The shape of the fluorescent lines also changes since scattered line photons form several Compton-shoulders which are very prominent especially for Compton-thick sources. Using a Monte Carlo method, we demonstrate the importance of Compton scattering for high column densities. For that purpose, we compare our results with existing absorption models that do not consider Compton scattering. These calculations will be implemented in a prospective version of the *tbabs* absorption model including an analytic evaluation of the strength of the fluorescent lines.

Keywords: interstellar absorption; Monte Carlo simulation.

1. Introduction

Some astronomical X-ray sources are deeply embedded in gas exceeding hydrogen column densities of $\sim 10^{24}\,\mathrm{cm}^{-2}$ (e.g. the X-ray binary IGR J16318-4848 [1]). The original spectrum emitted by such highly obscured systems is considerably modified by interactions between the radiation and the surrounding material. The flux below 10 keV is strongly reduced by photo absorption and the absorbed photons may be re-emitted as fluorescent lines. Compton scattering affects the spectral shape mainly due to down-scattering of high-energetic photons and has also an important impact on the fluorescent line profiles. Correctly interpreted, these modifications encode information about the composition, structure and geometrical formation of the source's environment. Current absorption models mostly neglect the effect of Compton scattering, though it is the dominant process for dense gas and high photon energies. For this reason, we present on a revised version of the *tbabs* [2] the absorption model which includes both Compton scattering and fluorescent line emission and is therefore appropriate to model the spectra of highly absorbed systems.

2. Computational method

The Monte Carlo method labels a class of computational algorithms that achieves numerical results by repeated random sampling. Applied to the problem of radiative transfer this means we simulate the random walk that a photon performs during its passage through a medium of a defined thickness. The absorbing gas is assumed to be neutral and has a constant density. The included interaction mechanisms between radiation and matter are photo absorption, fluorescent line emission, and Compton scattering. The photo absorption cross sections are taken from Verner & Yakovlev (1995) [3] and include all elements with $\mathrm{Z} \leq 30$. We consider also the emission of K-fluorescent lines according to the fluorescent yields from Kaastra & Mewe (1993) [4]. Compton scattering is simulated by using the Klein-Nishina formula and we follow all photons of the primary spectrum as well as the fluorescent photons until they leave the medium. In this manner, we are able to model scattering features like the Compton shoulders of the emission lines and the Compton-bump at moderate energies. A similar simulation for modeling the X-ray processing through a Compton-thick toroidal medium has already been provided by Murphy & Yaqoob (2009) [5]. Our aim is to provide a simple, geometrically flexible fitting model able to represent the scattering processes in highly obscured sources realistically.

3. Scattering features

To demonstrate the influence of Compton scattering on the spectral shape, we compare in Fig. 1 two ab-

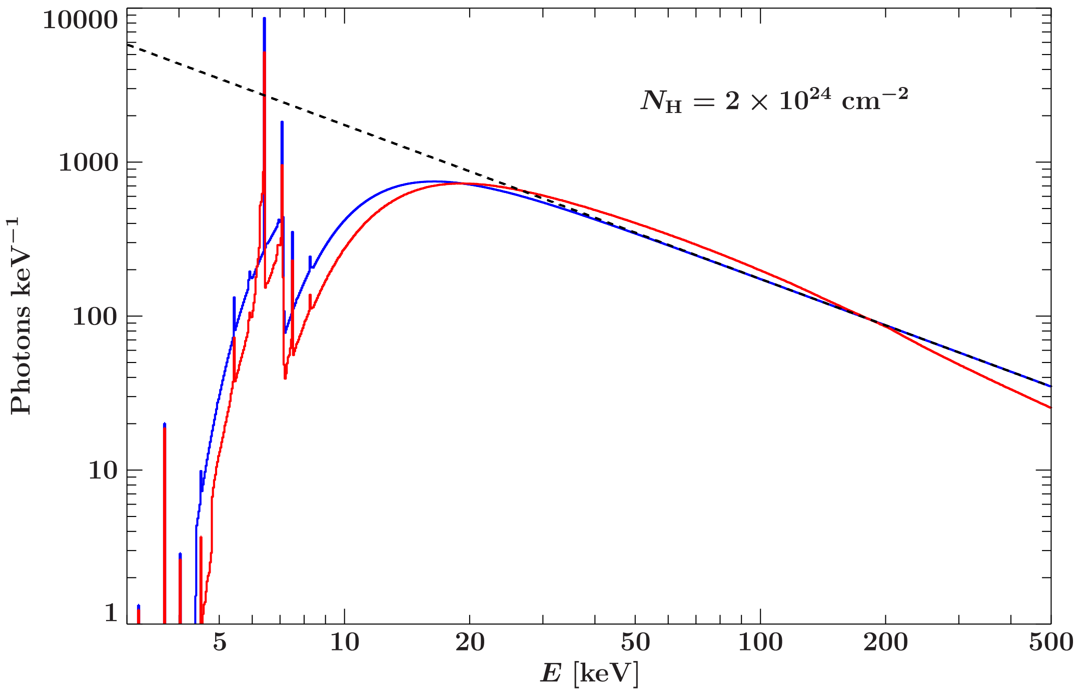

Figure 1. Absorbed spectra transmitted through a sphere for $N_H = 2 \times 10^{24}\,\mathrm{cm}^{-2}$. The red spectrum is calculated with considering Compton scattering, the blue one with including photo absorption only. The dashed line indicates the input spectrum.

sorbed spectra, the red spectrum simulated taking Compton scattering fully into account and the blue one considering only photo absorption. The dashed black line represents the input spectrum. Both spectra are modeled using a geometry where the photon source is located in the center of a spherical cloud with a radius equivalent to $N_H = 2 \times 10^{24}\,\mathrm{cm}^{-2}$. In contrast to the unscattered spectrum, which is indistinguishable from the input continuum above $\sim 20\,\mathrm{keV}$, the scattered spectrum shows a significant lack of photons above 200 keV. As the relative energy loss per scattering is proportional to the photon energy, the high energy photons are effectively down-scattered and accumulate at moderate energies forming the so-called Compton-bump between $\sim$ 30–100 keV. In addition, the strength of the fluorescent lines and also the overall flux in the low energy range are reduced again by Compton down-scattering. Figure 2 shows the iron band in detail. The profile of the iron K_α-line at 6.4 keV exhibits on its red side several Compton-shoulders consisting of line photons that are scattered once or multiple times. This feature has also been observed, e.g. in the spectrum of the massive X-ray binary GX 301-2 [6].

4. Geometry dependence

Depending on the distribution of the surrounding matter a different fraction of the radiation is either absorbed, scattered or escapes without interaction and therefore the shape of the reprocessed spectrum strongly depends on the geometry of the absorbing material. Figure 3 shows the transmitted spectra for the same column density but two different geometries, a spherical geometry with the primary source located at the center and a slab located between the observer and the source. The spectra are normalized at the iron K-edge energy. The ratio between the spectra (lower panel) illustrates the geometry induced differences in the Compton-shoulder and the Compton down-scattering at higher energies. Both the Compton-bump and the fluorescent lines are more pronounced for the spherical geometry. This is due to the different path length that a photon travels on average before it leaves the medium. Back-scattered photons still have a good chance to leave the spherical geometry on the other side but they are mostly absorbed in the slab case. Therefore, the averaged distance that a photon traverses is larger for the spherical geometry.

In Fig. 4 we compare the spectrum for pure Compton reflection with a transmitted spectrum. Again the spectra are normalized at the iron K-edge energy. The blue spectrum shows the reflected radiation from a semi-infinite slab averaged over all inclination angles. The red spectrum was calculated using again the spherical cloud geometry with a radius equivalent to $N_H = 1 \times 10^{24}\,\mathrm{cm}^{-2}$. This value was chosen for a better comparison because it results in a similar equivalent width of the iron K_α-line for both the reflected and transmitted case. In contrast to the transmitted spectrum, which is formed mainly by photo absorption, the shape of the reflected spectrum is almost exclusively determined by Compton back-scattering. The Compton-bump can be well seen at moderate energies. As forward scattering is the preferred process for high photon energies, the intensity decreases above $\sim 30\,\mathrm{keV}$.

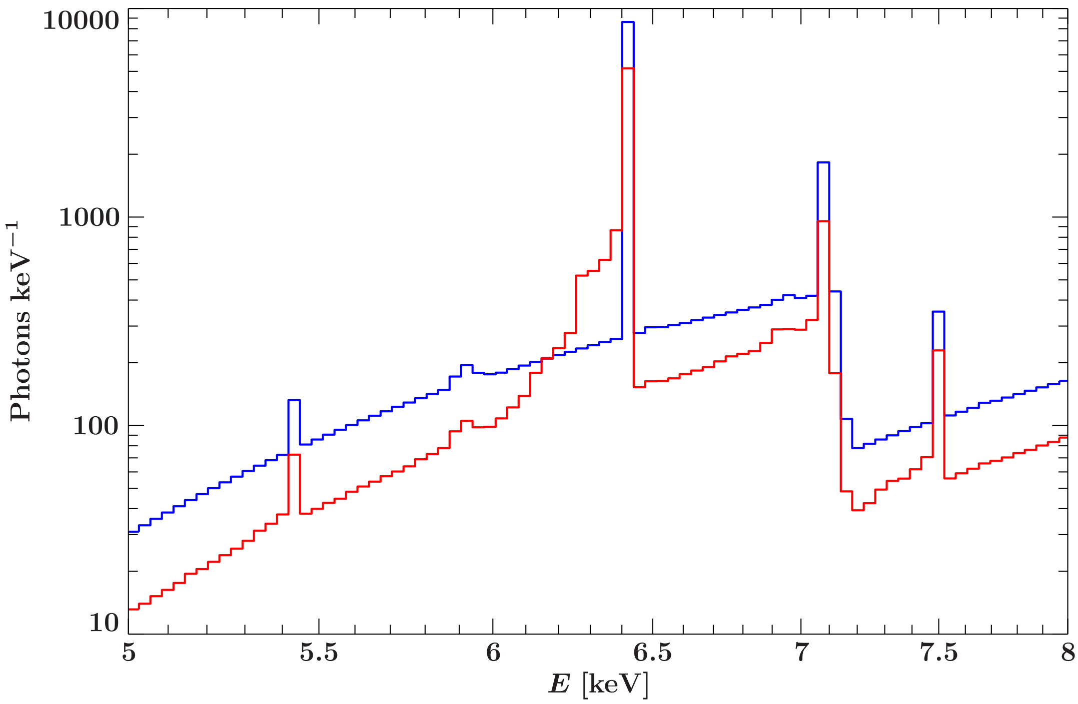

Figure 2. Same as Fig. 1 with a detailed view on the iron region.

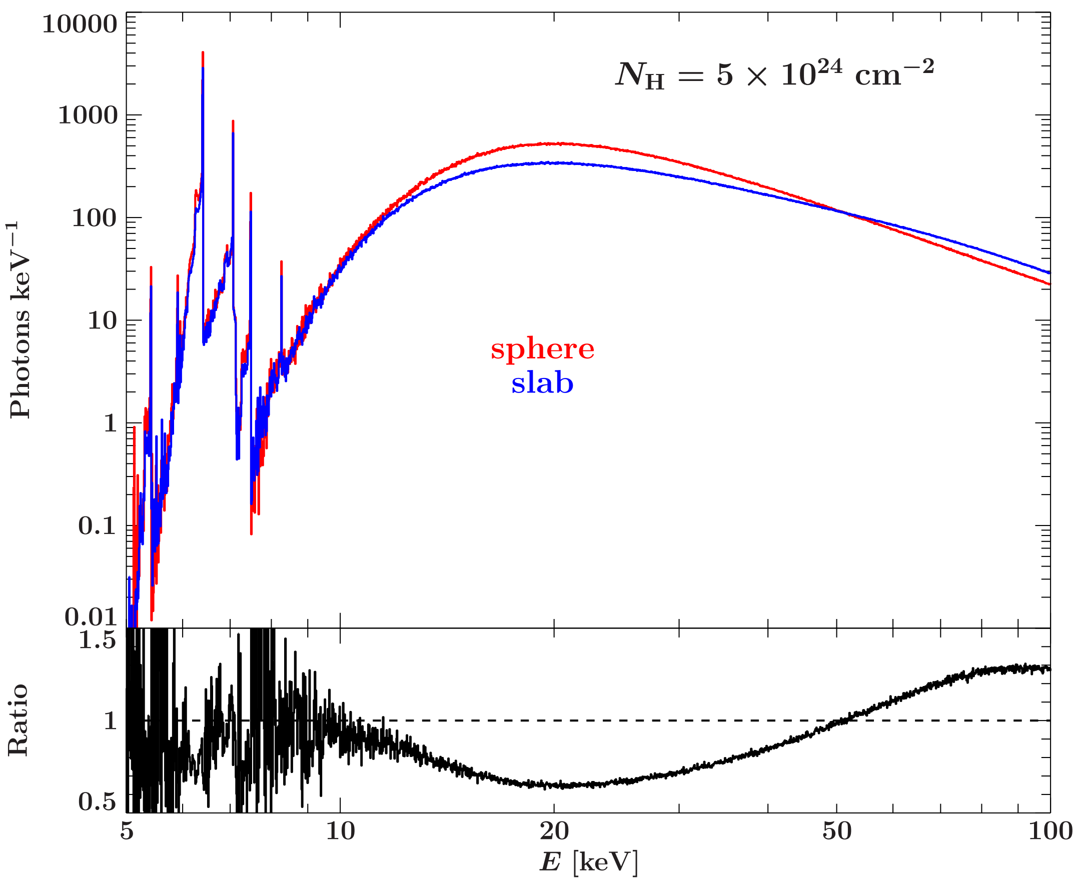

Figure 3. Absorbed spectra for transmission through a sphere (red) and though a slab (blue) both calculated for $N_{\mathrm{H}} = 5 \times 10^{24}\,\mathrm{cm}^{-2}$.

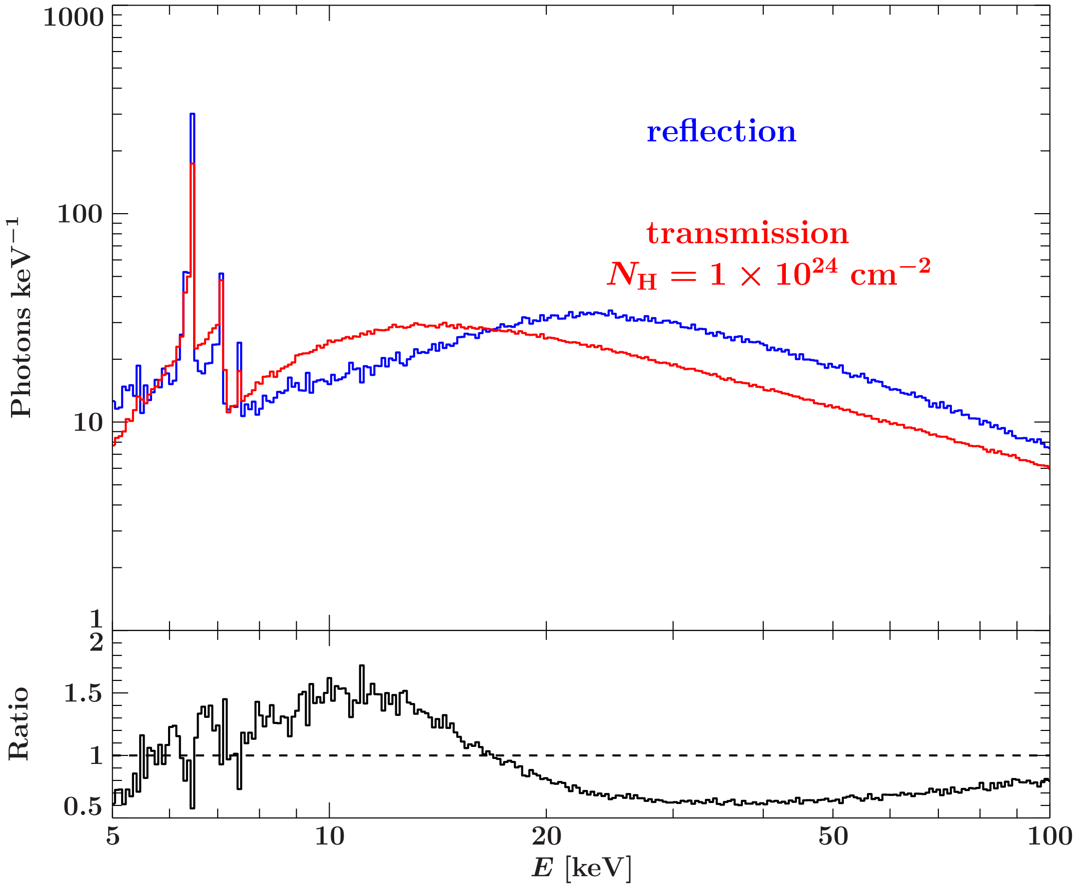

FIGURE 4. Spectra for transmission through a sphere (red) calculated for $N_H = 1 \times 10^{24}\,\mathrm{cm}^{-2}$ and reflection from a slab (blue).

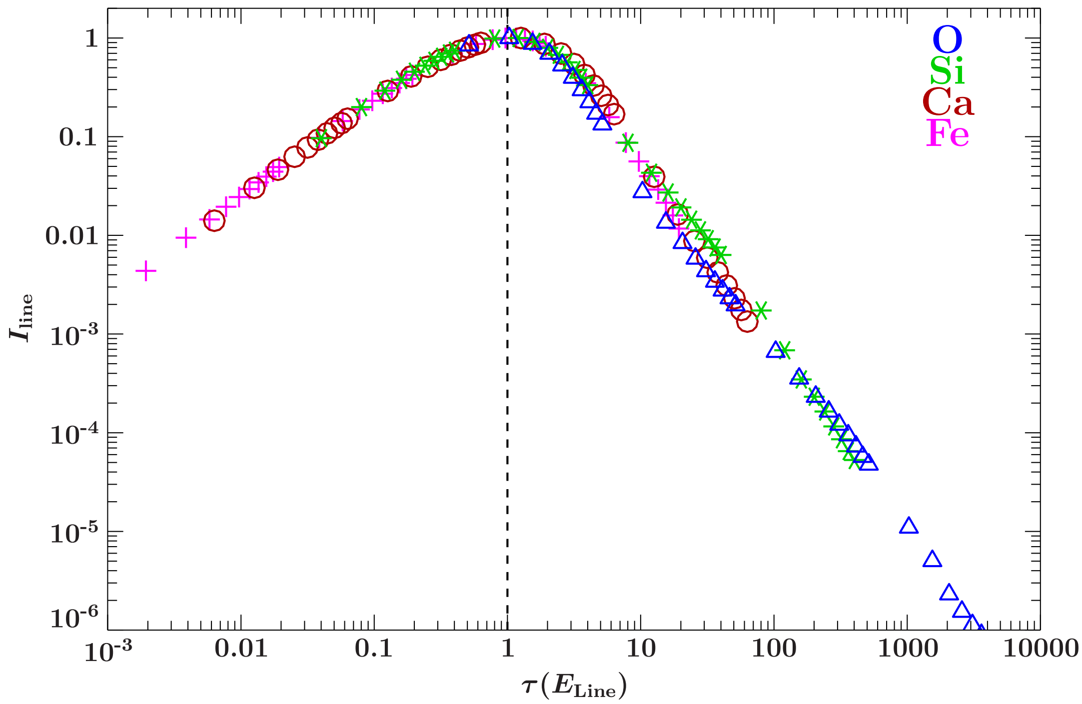

FIGURE 5. General line shape for a spherical geometry and for a monochromatic photon beam at $E = 10\,\mathrm{keV}$ as input.

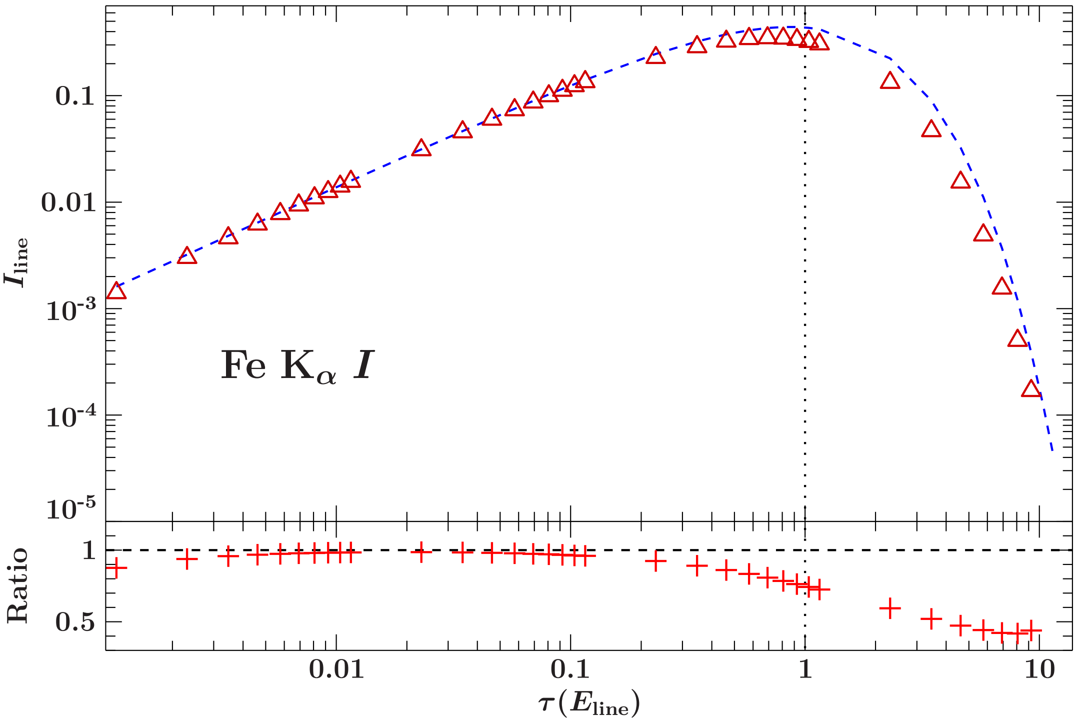

FIGURE 6. Modulation of the Fe K_α I-line.

5. Fluorescent lines

The strength of the fluorescent lines depends upon properties of the absorbing material such as its elemental composition and geometry. Assuming a spherical geometry, the line strength as a function of the column density is very similar for all lines. To demonstrate this we show in Fig. 5 the strength of the K_α-line of O, Si, Ca and Fe plotted against the optical depth given by

$$\tau(E_{\rm line}) = \sigma(E_{\rm line})N_{\rm H}$$

where $\sigma(E_{\rm line})$ is the sum of the photo absorption and Compton scattering cross section for the respective line energy. The dashed line marks the depth $\tau = 1$ from which a line photon interacts on average more than once before it escapes. Up to this limit, the line strength increases continuously for all elements and thereupon decreases again as a result of Compton down-scattering and new photo absorption.

The next step was to reconstruct the line shape analytically as a function of the optical depth. We assume for now a monochromatic input spectrum with intensity $I_{\rm in}$ and energy $E_{\rm in}$. Starting from the well-known formula

$$I_{\rm out}(E_{\rm in}) = I_{\rm in}(E_{\rm in})\mathrm{e}^{-\tau(E_{\rm in})}$$

we can describe the line strength simplified by

$$I_{\rm line}(E_{\rm line}) \propto I_{\rm in}(E_{\rm in})\big(1 - \mathrm{e}^{-\tau(E_{\rm in})}\big)\mathrm{e}^{-\tau(E_{\rm line})}.$$

The first term describes the number of line photons that was created within τ and the second term describes the subsequent absorption. In Fig. 6 we compare the analytic solution (blue dashed line) with the values for the iron K_α-line from the simulation (red triangles). The general evolution of the line strength is quite well described considering the simplicity of the function. The deviations for large optical depths comes especially from the interplay of isotropic line emission and anisotropic Compton scattering.

6. Outlook

Additionally to the efforts described here, two further updates will be implemented in a revised version of the *tbabs* absorption model:

(1.) higher resolution cross sections close to the absorption edges of neon, oxygen, and iron.

(2.) the addition of mechanisms to include laboratory measured cross sections for solids.

Test versions of these modifications will be available at `http://pulsar.sternwarte.uni-erlangen.de/wilms/research/tbabs`

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