X–ray spectra transmitted through Compton–thick absorbers

Giorgio Matt, Fulvio Pompilio & Fabio La Franca

Dipartimento di Fisica, Università degli Studi “Roma Tre”, Via della Vasca Navale 84, I–00146 Roma, Italy

Abstract

X–ray spectra transmitted through matter which is optically thick to Compton scattering are computed by means of Monte Carlo simulations. Applications to the BeppoSAX data of the Seyfert 2 galaxy in Circinus, and to the spectral modeling of the Cosmic X–ray Background, are discussed.

Key words: radiative transfer – galaxies: Seyfert – X-rays: general
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1 Introduction

The presence of large amount of “cold” (i.e. not much ionized, and substantially opaque in X–rays) matter around Active Galactic Nuclei is now a well established fact. For all Seyfert 2 galaxies observed in X–rays so far there is evidence for absorption in excess of the Galactic one. In a significant fraction of them, the column density of the absorbing matter exceeds $10^{24}$ cm$^{-2}$ (Maiolino et al. 1998), and the matter is therefore optically thick to Compton scattering. In a few objects, like NGC 1068 (Matt et al. 1997), the column density is so high that the X–ray photons cannot escape even in hard X–rays, being trapped in the matter, downscattered to energies where photoelectric absorption dominates, and eventually destroyed. In other cases, like NGC 4945 (Iwasawa et al. 1993; Done et al. 1996), Mrk 3 (Cappi et al. 1999) and the Circinus Galaxy (Matt et al. 1999), the column density is a few\,$\times\,10^{24}$ cm$^{-2}$, so permitting the transmission of a significant fraction of X–ray photons, many of them escaping after one or more scatterings. To properly model transmission through absorbers with these intermediate column densities, is therefore

1 E-mails: (matt,pompilio,lafranca)@fis.uniroma3.it
necessary to fully take into account Compton scattering. This has been done in an analytical, approximated way by Yaqoob (1997), but his model is valid only below \( \sim 15 \) keV, a painful limitation after the launch of BeppoSAX, which carries a sensitive hard X-ray (15-200 keV) instrument, and in view of future missions like Astro-E and Constellation-X.

We have therefore calculated transmitted spectra by means of Monte Carlo simulations. The code is, as far as physical processes are concerned, basically that described in Matt, Perola & Piro (1991). A spherical geometry, with the X-ray source in the centre, has been assumed, while the element abundances are those tabulated in Morrison & McCammon (1983). Photoelectric absorption, Compton scattering (in a fully relativistic treatment) and fluorescence (for iron atoms only) are included in the code. Photon’s path are followed until either the photon is photoabsorbed (and not re-emitted as iron fluorescence) or escapes from the cloud.

Spectra have been calculated for 31 different column densities, ranging from \( 10^{22} \) to \( 4 \times 10^{24} \) cm\(^{-2}\). In order to be independent of the shape of the primary radiation, transmitted spectra for monochromatic emission have been calculated, with a step of 0.1 keV below 20 keV, and 1 keV above. A grid has then been constructed, which can be folded with the chosen spectral shape.

2 Transmitted spectra. Comparison with simple absorption models

To illustrate the effects of including the Compton scattering in the transmission spectrum, we show in Figs 1-5 (which refer to column densities of \( 10^{23} \), \( 3 \times 10^{23} \), \( 10^{24} \), \( 3 \times 10^{24} \) and \( 10^{25} \) cm\(^{-2}\), respectively), the results of the Monte-Carlo simulations (solid lines), along with the results when only photoelectric absorption (dotted lines) or both photoelectric and Compton absorption without scattering (dashed lines) are included. The first case is unphysical, and it is shown here only for the sake of illustration; the second case would correspond to absorption by matter with a negligible covering factor to the primary source (i.e. a small cloud on the line of sight), a physically possible but highly unlikely situation, at least for Seyfert galaxies (the fraction of Compton–thick sources is estimated to be at least 30%, Maiolino et al. 1998, and then the covering fraction of the matter must be significant). The injected spectrum is a power law with a photon index of 2 and an exponential cut–off at 500 keV, as typical for Seyfert galaxies (even if the latter parameter is at present poorly known). As expected, our curves lie below the dotted curves (because of the larger absorption especially above \( \sim 10 \) keV, where the Compton cross section starts dominating over the photoelectric cross section), and above the dashed curves (because of the extra radiation provided by the scattering of photons into the line of sight). The effect is dramatic, especially for large column densities and
Fig. 1. Transmitted spectra (in $EF(E)$) for a column density $N_H = 10^{23}\text{ cm}^{-2}$. The solid line refers to the Monte Carlo results discussed in this paper. The dotted line is for photoelectric absorption alone (an unphysical situation, presented here only for the sake of comparison); the dashed line for complete (photoelectric and Compton scattering) absorption, as for a small cloud on the line of sight.

3 Applications. I. The Circinus Galaxy

As a first application, let us discuss the case of the Circinus Galaxy. Matt et al. (1999) analyzed the BeppoSAX observation of this source and found a clear excess in hard X-rays (i.e. in the PDS instrument) with respect to the best fit medium energy (i.e. LECS and MECS) spectrum (which, in turn, was in good agreement with the ASCA result, Matt et al. 1996). The excess is best explained assuming that the nuclear emission is piercing through material with moderate Compton-thick (i.e. between $10^{24}$ and $10^{25}\text{ cm}^{-2}$, see previous section) column density. Compton scattering must therefore be taken into account in modeling the emerging spectrum, not only in absorption but also in high energies.
Fig. 2. As for Figure 1, but for $N_H = 3 \times 10^{23}$ cm$^{-2}$.

emission, as there is clear evidence of large amount of reflection too, suggesting a fairly large solid angle subtended by the cold matter to the primary source. The fit with the model described here yields the parameters of the transmitted component reported in Table 1 (model 1). Model 2 in the same table refers to the fit with a pure absorption model (photelectric plus Compton). Both models are statistically acceptable (reduced $\chi^2 \sim 1$), but the differences in the best fit parameters are significant, leading to dramatically different (i.e. two orders of magnitude) X–ray nuclear luminosities.

4 Applications. II. The hard X–ray Background

The origin of the thermal–like, $\sim 40$ keV spectrum (Marshall et al. 1980) of the hard Cosmic X–ray background (XRB) has remained unexplained for many years. In 1989, Setti & Woltjer proposed an explanation in terms of a mixture of obscured (i.e. Seyfert 2s) and unobscured (i.e. Seyfert 1s) AGN. Following this idea, many authors developed synthesis models for the XRB (e.g. Madau, Ghisellini & Fabian 1993, 1994; Matt & Fabian 1994; Comastri et al. 1995),
Fig. 3. As for Figure 1, but for $N_H = 10^{24}$ cm$^{-2}$.

Table 1
Parameters of the best fit models. Model 1 includes Compton scattering, model 2 only absorption. The primary spectrum is a power law with photon index $\Gamma$ and a high energy cut–off: $E_C$ is the corresponding e–folding energy. $A$ is the density flux at 1 keV.

|                  | 1    | 2    |
|------------------|------|------|
| $N_{H,1}$ (10$^{24}$ cm$^{-2}$) | 4.3  | 6.9  |
| $A$ (ph cm$^{-2}$ s$^{-1}$ keV$^{-1}$ at 1 keV) | 0.11 | 15.4 |
| $\Gamma$         | 1.56 | 1.58 |
| $E_C$ (keV)      | 56   | 38   |
| $L$(2-10 keV) (erg s$^{-1}$) | $10^{42}$ | $1.5\times10^{44}$ |
Fig. 4. As for Figure 1, but for \( N_H = 3 \times 10^{24} \text{ cm}^{-2} \).

and nowadays this explanation is widely considered as basically correct.

To model the spectrum of the XRB it is necessary to include all the relevant ingredients, and a correct transmission spectrum is one of them because, as remarked above, Compton–thick sources are a significant fraction of all Seyfert 2s. To our knowledge, out of the many papers devoted to fitting the XRB, the transmission component has been properly included only by Madau, Ghisellini & Fabian (1994). Here we do it again, to highlight and discuss the differences with models in which only absorption is included. In Fig. 6, we show the integrated local spectrum of Seyfert 1 galaxies (dotted curve), of Seyfert 2 galaxies (lower dashed and solid curves) and of the sum of Seyfert 1 and 2 galaxies (upper dashed and solid curves). The spectrum of Seyfert 1 galaxies is described by a power law with a photon spectral index of 1.9 and an exponential cut–off with e-folding energy of 400 keV; a Compton reflection component, corresponding to an isotropically illuminated accretion disk observed at an inclination angle of 60°, is also included. According to unification models, the spectrum of Seyfert 2 galaxies is assumed to be intrinsically identical to that of Seyfert 1s, but seen through obscuring matter. The solid lines in the figure refer to a synthesis model in which the transmitted component is included, while
in the dashed ones only absorption is considered. Type 2 sources are assumed to outnumber type 1 sources by a factor of 4, independently of the luminosity. The adopted distribution of column densities of the absorbing matter for the Seyfert 2s is: \( \frac{dN}{d\text{Log}(N_H)} \propto \text{Log}(N_H) \), from \( 10^{21} \) to \( 4 \times 10^{25} \text{ cm}^{-2} \). The fraction of Compton–thick sources is then about 1/3, in agreement with the estimate of Maiolino et al. (1998). The two total spectra differ significantly above 10 keV, the spectrum including the transmission component being about 20% higher at 30 keV.

The best fit spectrum to the XRB (HEAO-1 data, Marshall et al. 1980), obtained after evolving the local spectrum of Seyfert galaxies to cosmological distances, following Boyle et al. (1994), is shown in Fig.7. Different descriptions of the pure luminosity evolution scenario do not change significantly the results. The study of both the spectral shape of the XRB and the source counts in different scenarios, including e.g. density evolution, is beyond the scope of the present work, and is deferred to a forthcoming paper (Pompilio et al., in preparation). Apart from the highest energy part of the spectrum, where the fit is not very good (suggesting either that an exponential cut–off is not a good description of the spectrum of Seyfert galaxies, or that there is not a universal
Fig. 6. The integrated local spectrum of Seyfert 2s (with, solid line, and without, dashed line, the transmitted component), of Seyfert 1s (dotted line) and total. See text for detail.

value of such a parameter, as actually is emerging from BeppoSAX observations: see e.g. Matt 1998), and the lowest part (where contributions from other classes of sources, like Clusters of Galaxies, may be relevant), the agreement between the data and the model is acceptable. The soft X–ray source counts are also well reproduced, while the hard (5–10 keV) counts (Fiore et al., in preparation; Comastri et al. 1999) are somewhat underestimated, but still marginally consistent with the data. The complete model and the detailed analysis will be discussed elsewhere (Pompilio 1999; Pompilio et al., in preparation).

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