ABSORPTION AND SCATTERING IN THOMSON-THICK MEDIA

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ABSTRACT

Using a Monte Carlo method, we study Compton scattering and absorption of X-rays and gamma-rays in cold media. We consider both reflection and transmission of X-rays and gamma-rays. First, we consider reflection from a slab of large optical depth, for which we derive analytic approximations to energy and angle-dependent Green's functions. Second, we consider transmission of X-rays and gamma-rays through a spherical shell of an arbitrary optical depth, for which we derive energy-dependent Green's functions. The Green's functions take into account Compton scattering with Klein-Nishina effects as well as absorption with an arbitrary dependence on energy (which allows to treat media with an arbitrary ionization state and chemical composition).

Our treatment of reflection takes into account the angular dependence, which is crucial in the hard X-ray and soft gamma-ray range. The effect is especially important for modeling spectra of Seyfert 1's and galactic black hole sources, in which Compton reflection occurs commonly. On the other hand, our transmission Green's functions allow to treat Thomson-thick plasmas, which commonly occur in Seyfert 2's.

1. INTRODUCTION

We use the Monte Carlo method of White et al. (1988) to calculate X-ray and gamma-ray spectra reflected by a semi-infinite, plane-parallel medium of cold electrons irradiated by photons with an isotropic angular distribution corresponding to emission of an optically thin corona, and as a function of observing angle. We fitted angle-dependent Green's functions with simple, useful formulae, which may be well applied to modelling spectra with reflection component commonly observed in Seyfert 1's.

We also calculate spectra transmitted through a geometrically thin shell as a function of Thomson depth of the shell. The work on fitting Green's functions dependent on the incident photon energy and Thomson depth with analytic formulae is in progress. The formulae will be applicable to modelling transmission spectra in Syfert 2's where optically thick molecular tori are observed.

In solar composition matter, Compton scattering is accompanied by bound-free absorption, which gives important contribution up to energies of about 40keV, where Compton cross-section is significantly relativistic, and no monochromatic approximation can be used. We developed a simple treatment the effect of bound-free absorption on Green's functions for Compton scattering.

2. ANGLE-DEPENDENT COMPTON REFLECTION

The first-order Green function for Compton reflection has been calculated by Hua & Lingenfelter (1992). The total Green functions are disscused in detail in Magdziarz & Zdziarski (1995), see Fig. 1.

The reflected spectra for a typical Syfert 1's incident spectrum are presented on Fig. 2 for various viewing angles. The characteristic hardening of the high-energy part of the spectrum for large viewing angles (small μ) is due to increasing contribution from photons scattered nearly forward (i.e., grazing scattering medium) for which wavelength shift is nearly zero. It is also noticable on the top panel of Fig. 1. On the other hand, the reflected spectrum hardens at the low energy part for small viewing angles, since the most of photons are back scattered in this case, and thus strongly shifted to lower energies with $\Delta y \approx 2$ (see Fig. 1, the bottom panel). This also means that the scattering takes place at higher energies where the single scattering albedo is significantly higher.

3. PHOTON TRANSMISSION THROUGH COMPTON-THICK MEDIA

Compton scattering of photons emitted from a point source through a geometrically-thin shell can be nearly equivalently considered as a scattering of perpendicullarly normal-incidence photons by a plane-prallel, semi-infinite medium. This makes the problem easier in the case of the first-order scattering when the single-scattering distribution for a plane-parallel problem may be simply integrated:

$$g_1(y_0,\Delta y)=\int \frac{\mathrm{d}\phi}{2\pi}\,\mathrm{d}\mu\,\mathrm{d}\mu_i f(y_0,\Delta y)\delta(1-\Delta y-\sqrt{1-\mu_i^2}\sqrt{1-\mu^2}\cos\phi-\mu_i\mu)\delta(1-\mu_i)$$

where

$$f(y_0,\Delta y)=\frac{\left(\frac{y_0}{y_0+\Delta y}\right)^2\left(\frac{y_0+\Delta y}{y_0}+\frac{y_0}{y_0+\Delta y}+(1-\Delta y)^2-1\right)}{y_0\left((1-2y_0(1+y_0))\ln\left(\frac{2+y_0}{y_0}\right)+4y_0+2\frac{1+y_0}{(2+y_0)^2}\right)}$$

is the well-known energy distribution of Compton scattered photon, μ_i is the incident angle, and μ is the scattering angle. Since in this geometry only forward scattered photons escape after the first scattering, the maximum wavelength shift in the first-order Green's function is $\Delta y = 1$. The higher-order scatterings are analytically not integrable. The first-order Green's functions are presented on Fig. 3, together with the total Green's functions from Monte Carlo simulations. Noticable disscontinuities of the derivative are due to the contribution from the second-order scattering, and higher orders extend Green's function smoothly to lower energies.

It can be noticed on Fig. 3 that the diffusion limit is attained in a shell of the Thomson thickness of $\tau_0 = 30$ for incident photons of energy $x_0 < 1$, but not for higher energies, where the Klein- Nishina cross-section is too small. The dashed line on Fig. 4 shows the range of validity of the diffusion approximation. The range where the first-order Green's function may be used alone is marked with dotted line.

The transmitted spectra for typical incident Syfert 1's spectrum are presented on Fig. 5 for various Thomson depths of the shell, and compared with the spectrum which would result from absorption by both the bound-free and the Compton processes. The transmitted spectra are much above the spectrum from that simple approximation because scatterd photons are not removed from the system but rather continue to scatter. The effect is stronger for higher Thomson depth of the shell because the contribution from higher order scatterings increases,

and a characteristic shape with two maxima is noticeble. The higher-energy maximum is due to Klein-Nischina effect, and the lower-energy one is from diffusing photons.

4. THE IMPACT OF ABSORPTION ON GREEN'S FUNCTION

Since in general case Green's function can be decomposed into contributions from each order of scattering (cf. Illarionov et al. 1979):

$$G(y_0, \Delta y) = \sum_{i=1}^{\infty} g_i(y_0, \Delta y),$$

and absorption remove photon from the medium with a probability determined by a single scattering albedo at each scattering:

$$\lambda(y) = \frac{\sigma_{Comp}(y)}{\sigma_{Comp}(y) + \sigma_{bound-free}(y)},$$

Green's function in the presence of absorption may be written as:

$$G_{abs}(y_0, \Delta y) = \sum_{i=1}^{\infty} g_i(y_0, \Delta y) \prod_{k=1}^{i} \bar{\lambda}_k(y_0),$$

where $\bar{\lambda}_k$ is an effective single scattering albedo over the distribution of photons after k scatterings. Since the maximum of photon distribution in k-order appears at $\Delta y \approx k$ (relativistic effects shift the maximum to lower values of Δy), usually correct approximation is $\bar{\lambda}_k(y_0) \approx \lambda(y_0 + i - 1)$. This allow to factorize Green's function as:

$$G_{abs}(y_0, \Delta y) \approx G(y_0, \Delta y) \exp\left(\int_0^{\Delta y - 1} \mathrm{d}k \ln\left(\lambda(y_0 + k)\right) \right).$$

The first-order Green's function, for which the above equation fails, usually may be calculated separately, since it is influenced by absorption with a simple factor of $\lambda(y_0)$.

This method of approximation was used with neutral absorption given by Bałucińska & McCammon (1992) to calculate reflection spectra presented on Fig. 2.

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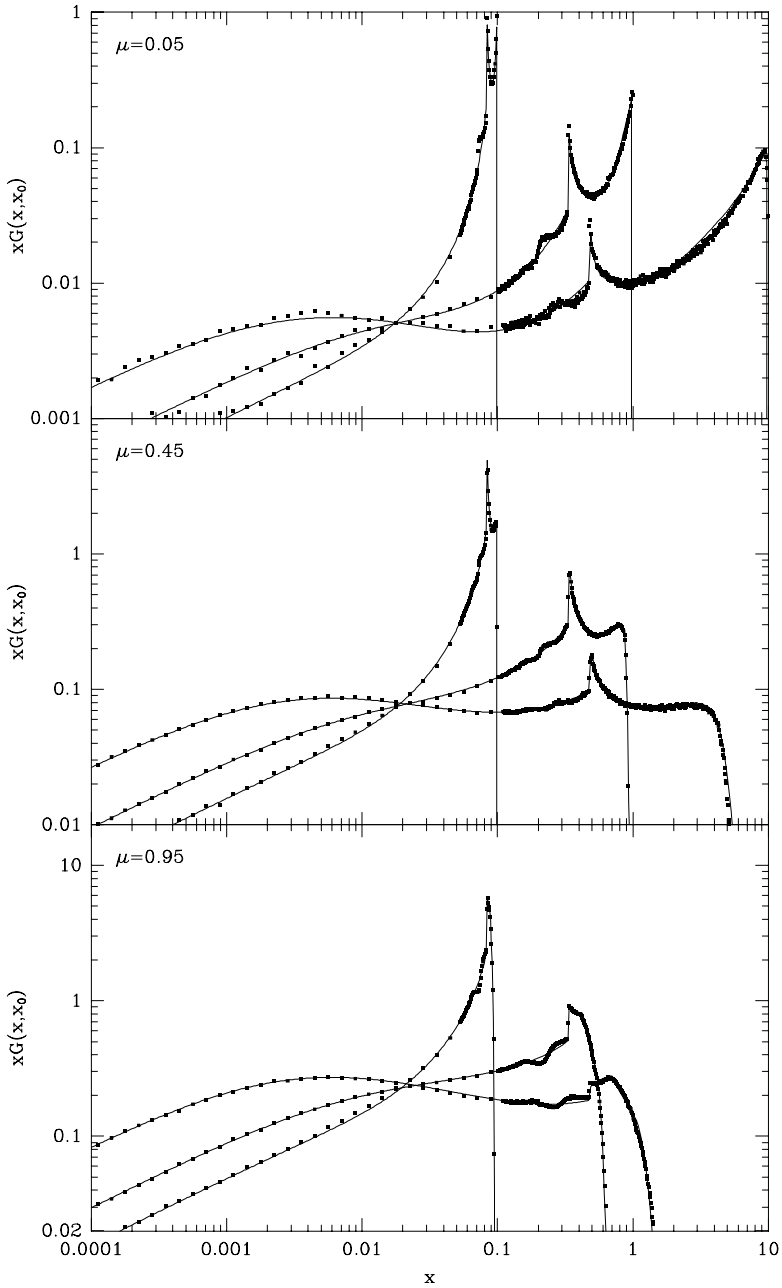

FIG. 1. Green's functions for Compton reflection of incident photons of energy $x_0 = 0.1$, 1, 10 ($x \equiv h\nu/m_e c^2$) from a plane-parallel, semi-infinite medium of large optical depth, observed at angle $\mu = 0.05$, 0.45, 0.95 (μ is the cosine of the inclination angle). Points indicate results of the Monte Carlo simulations, while solid curves show fits by Magdziarz & Zdziarski (1995).

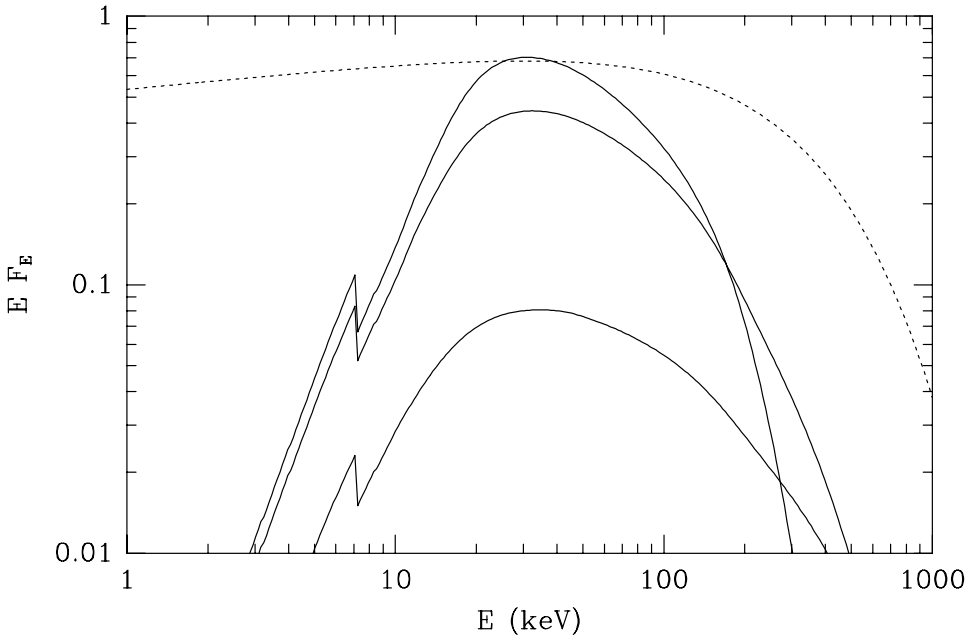

FIG. 2. The reflected spectra (solid curves) calculated using Green's functions by Magdziarz & Zdziarski (1995) for a power-law spectrum with $\alpha = 0.9$ and an exponential cut-off at 300keV (dotted curve) incident on a plane-parallel, semi-infinite, and optically thick medium. The vieving angles correspond to $\mu = 0.05$, 0.25, 0.45, 0.95.

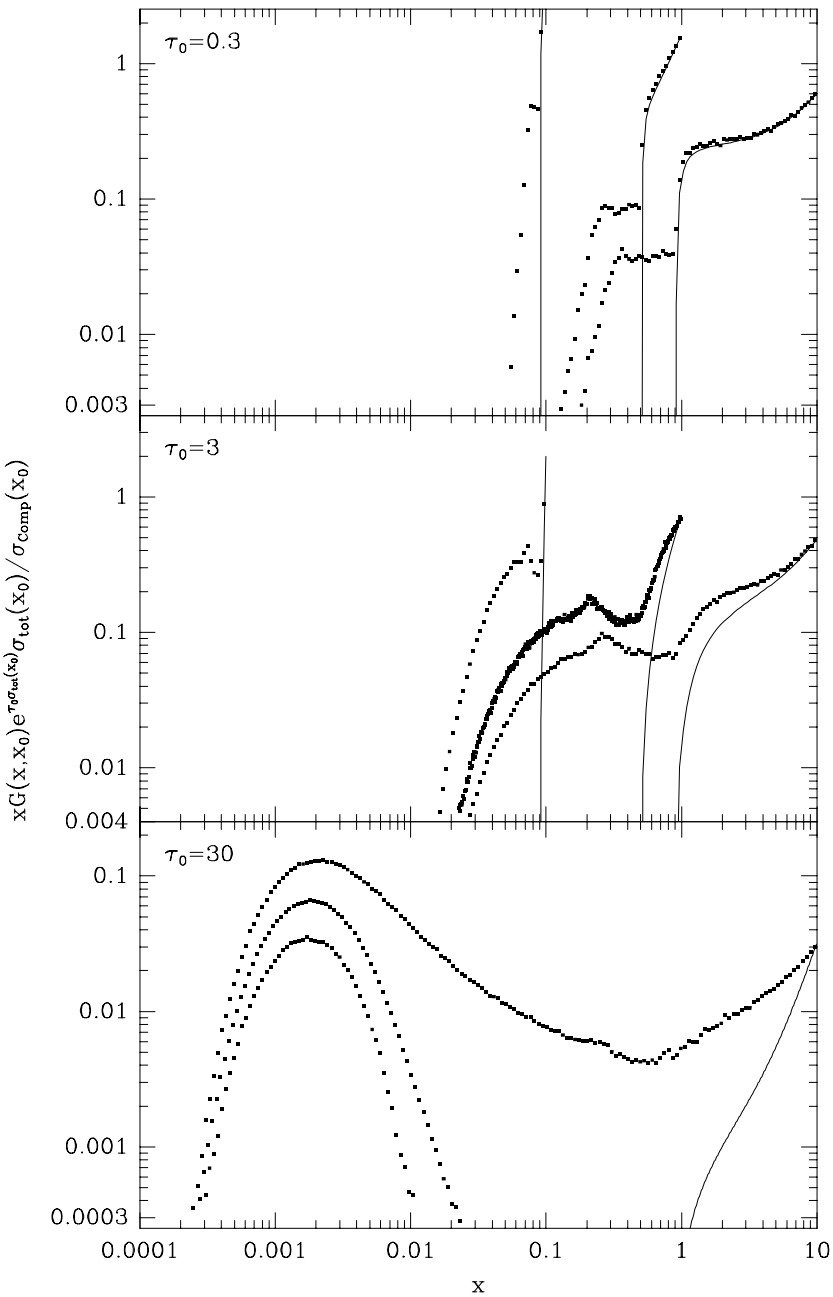

FIG. 3. Green's functions for Compton scattering of incident photons of energy $x_0 = 0.1$, 1, 10 ($x \equiv h\nu/m_e c^2$) by a geometrically thin shell of the optical Thomson thickness $\tau_0 = 0.3$, 3, 30. Points indicate results of Monte Carlo simulations, while solid curves show contribution from the first-order scattering. The Green's functions were normalized to the number of photons scattered in the first order.

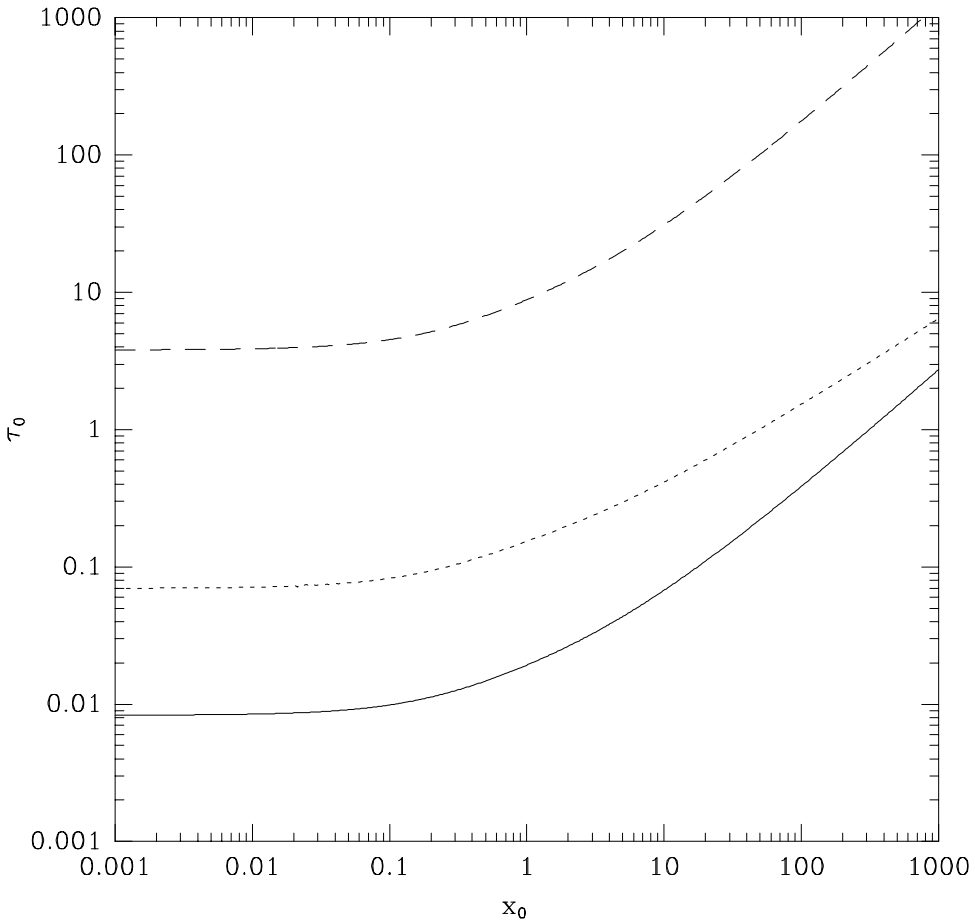

FIG. 4. Limits of the Thomson optical thickness for 1 per cent photons scatterd by a geometrically thin shell (solid line), and 1 per cent photons scattered more than ones (dotted line). The dashed curve shows a limit of 1 per cent photons transmitted without scattering. The area above this curve corresponds to Compton scattering well-described by the diffusion approximation.

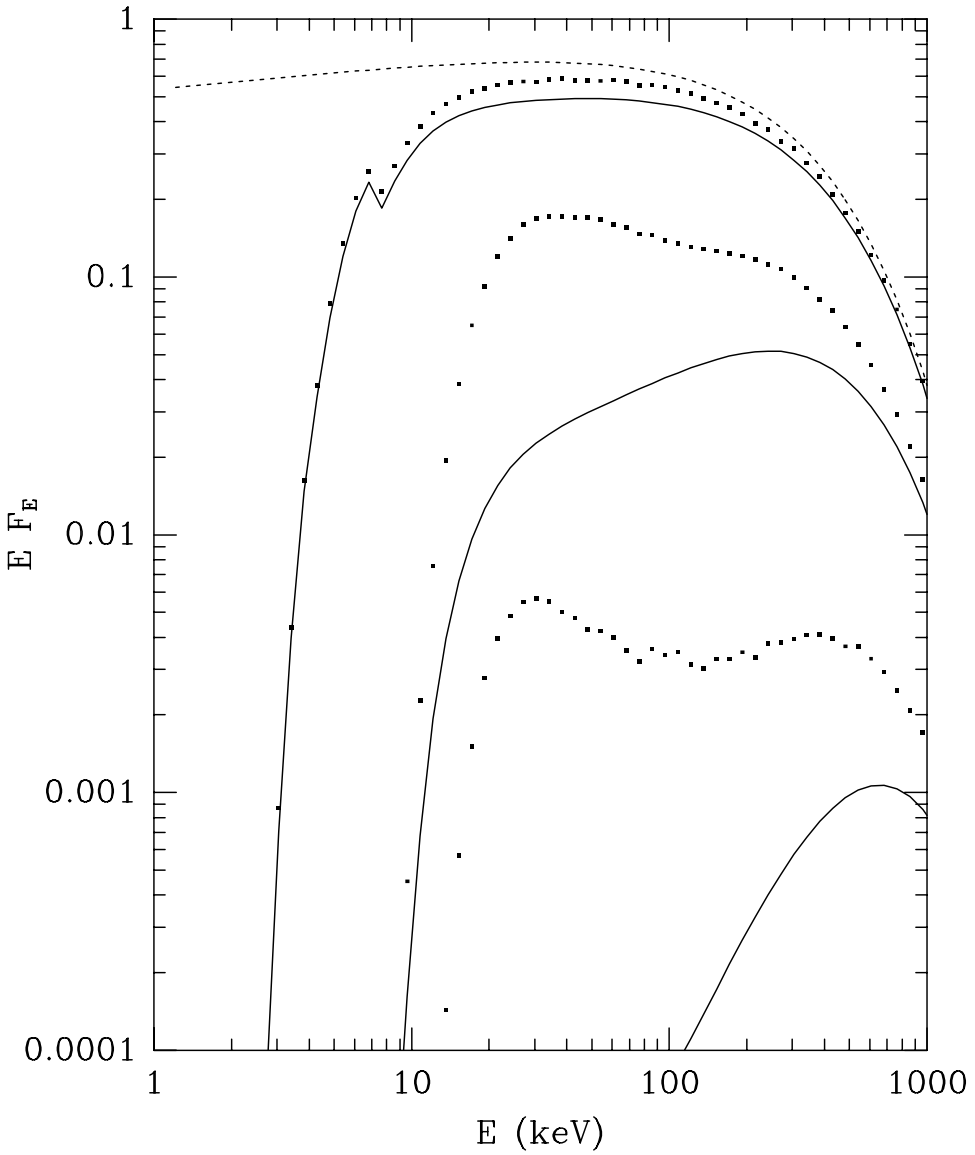

FIG. 5. The transmitted spectra (points) calculated with the Monte Carlo method for a power-law ($\alpha = 0.9$) spectrum with an exponential cut-off at 300 keV (dotted curve) incident on a geometrically thin shell of optical Thomson thickness of $\tau_0 = 0.3$, 3, 10. Solid curves show the incident spectrum multiplied by $\exp[-\tau_0(\sigma_{bound-free}(E) + \sigma_{Compton}(E))]$ (i.e., for the monochromatic absorption law).