REFLECTION AND REPROCESSING IN IN BLACK HOLE BINARIES AND SEYFERT GALAXIES

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The emission from galactic black holes and Seyfert galaxies is generally understood in term of two-phase models (Haardt & Maraschi 1991, 1993). Such models postulate that a hot plasma ($\sim 10^9$ K) is coexisting with relatively colder material ($\sim 10^6$ K) in the inner part of the accretion flow. We present the first simulated broad-band spectra produced by such a system and accounting for all the aspects of radiative coupling between the two phases. Indeed, our treatment accounts simultaneously for energy balance and Comptonisation in the hot phase, together with reflection, reprocessing, ionization and thermal balance in the cold phase. This was made possible by coupling three radiative transfer codes: a non-linear Monte-Carlo code, a photo-ionization code TITAN, and a linear Monte-Carlo code NOAR.

1 Introduction

At least two distinct media are required in order to produce the main features observed in the broad band spectra of active galactic nuclei (AGN) and black hole binaries (BHBs) in the low/hard state. Their hard X-ray emission exhibits a power-law spectrum cutting-off at a few hundred keV, which is generally interpreted as thermal Comptonisation spectra in a very hot ($\sim 10^9$ K) optically thin plasma with Thomson depth $\tau_{\rm T} \sim 1$ (Sunyaev & Titarchuk 1980). The big blue bump observed in the UV spectra of Seyfert galaxies (Walter & Fink 1993), as well as the soft X-ray excess in BHBs (e.g. Baluncinska-Church et al. 1995) are indicative of thermal emission from optically thick and much colder material with temperature in the range 10^5–10^7 K. The presence of relatively cold material in the innermost part of the accretion flow is corroborated by the existence of reflection features in the X-rays such as the Fe fluorescence line around 6.4 keV and a reflection bump peaking at about 30 keV (George & Fabian 1991, Nandra & Pounds 1994).

The nature and geometry of these two phases are uncertain. The cold medium is generally believed to constitute an accretion disc (Shakura & Sunyaev 1973), alternatively it could consist of cold dense clouds located inside or around the hot plasma (Rees 1987, Collin-Souffrin et al. 1996, Malzac 2001). The hot phase could constitute the accretion disc corona (Svensson & Zdziarski 1994, Zycki et al. 1995, Sincell & Krolik 1997, Różańska & Czerny 2000, and ref. therein) or the hot inner part of the accretion disc itself (Shapiro & Lightman 1976).

It has been soon realized that, if close from each other, the hot and the cold phases should be strongly radiatively coupled. This led to the development of two-phase models (Haardt & Maraschi 1991, 1993), where the cold phase constitutes the main source of seed photons for the Comptonisation process. The temperature in the hot phase, and thus the detailed shape of the high energy spectrum, is controlled mainly by the flux of soft cooling photons. On the other hand, the thermal reprocessing of the high energy radiation impinging on the cold phase provides a dominant contribution to soft emission from the cold phase.

Due to the complexity of the Comptonisation process, the importance of geometric effects, and the requirement of taking accurately into account the coupling between the two phases, it was necessary to develop sophisticated numerical codes in order to compute the detailed spectrum produced by the two-phase system in different configurations (Stern et al. 1995a, Poutanen & Svensson 1996).

The methods developed in this context, such as the non-linear Monte-Carlo method (Stern et al. 1995b), provide an accurate treatment of the hot phase emission in energy balance. On the other hand, the emission from the cold phase is not detailed: a pure blackbody spectrum with a fixed temperature and reflection on neutral material are generally assumed.

Actually the emission due to X-ray reprocessing in the cold phase differs widely from a simple blackbody, in particular there is a complex line emission. Moreover, due to the hard X-ray irradiation, a ionized skin is likely to form on the surface layers of the cold material (Ross & Fabian 1993, Collin-Souffrin et al. 1996, Nayakshin et al. 2000, Ballantyne et al. 2001). This ionized material affects the line emission as well as the shape and amplitude of the reflection component (Zycki et al. 1994, Dumont et al. 2000, Nayakshin et al. 2000, Nayakshin & Kallman 2001). Ionization is also likely to affect the equilibrium in the hot phase. Indeed the hard X-ray albedo for ionized material is larger and, as a consequence, the flux of thermal reprocessed soft photons is lower, affecting the temperature in the hot plasma.

The first attempts to include these effects in the two-phase model calculations were very rough (e.g. Nayakshin & Dove 2001). Indeed, a detailed self-consistent computation of the emission from irradiated material is an heavy task. It requires to solve the radiative transfer equations in the cold medium taking into account the energy and ionization balance including all the atomic processes. Another difficulty comes from the fact that the cold material is optically thick and its temperature and ionization structure at equilibrium is strongly inhomogeneous.

The detailed computation of the structure and spectrum of irradiated optically thick material was performed by coupling the photo-ionization code TITAN and the Monte-Carlo code NOAR (accounting for Compton scattering) (Dumont et al. 2000). It enabled to show the importance of an accurate radiative transfer treatment for the irradiated cold material emission.

However, in these calculations the feedback from the cold radiation on the hot phase equilibrium was not considered. As irradiating spectrum, a simple power-law with a fixed slope was assumed.

Here we add a self-consistent treatment of the hot phase emission by coupling the TITAN/NOAR codes with a third code based on the Non-Linear Monte-Carlo method (Malzac & Jourdain 2000).

This enables us to propose the first full treatment of the radiative coupling, accounting accurately and self–consistently for both the hot and cold phase emission. We demonstrate the important effects of our detailed treatment of reprocessing on the equilibrium spectrum.

2 The NOAR/TITAN and NLMC codes

TITAN is a code designed for hot media (T> a few 10^4 K) optically thick to Compton scattering. It computes the structure of a plane-parallel slab of gas in thermal and ionization equilibrium, illuminated by a given spectrum on one or two sides of the slab (Dumont et al. 2000). It takes into account the returning flux using a two-stream approximation to solve the transfer in the lines (instead of the escape probability formalism). This code is coupled with a Monte Carlo code, NOAR, which takes into account Compton and inverse Compton diffusions in any geometry (Abrassart 1998). NOAR uses the local fractional abundances and the temperature provided by TITAN, while NOAR provides TITAN with the local Compton gains and losses in each layer.

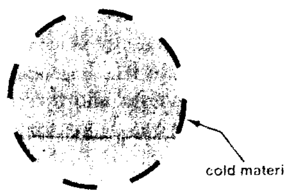

Figure 1: The proposed method can apply for any kind of geometry of the two-phase system. Here we will follow the picture proposed by Collin-Souffrin et al. (1996) where the hot phase constitutes a sphere at the center of the accretion flow and surrounded by cold material possibly in the form of clouds or filaments. For simplicity, we assume that the cold material is spherically distributed at the sphere surface.

The Compton heating-cooling rate is indeed dominated by energy losses of photons at high energies (> 25 keV), not considered by TITAN. The coupling thus allows to solve consistently both the global and the local energy balance. NOAR also allows to compute the fluorescence line profiles which are significantly Compton-broadened in case of strong illumination, and the comptonized reflection spectrum above 25 keV.

In parallel, we use the NLMC code described and tested in Malzac & Jourdain (2000) based on the Non-Linear Monte-Carlo method proposed by Stern et al. (1995b). This code computes the comptonised spectrum and energy balance in the hot phase. The radiation field is represented using about 10^4 pseudo-particles called Large Particles (LP). Each LP represents a number of photons with identical characteristics (energy, position, direction of propagation,...). These LPs are tracked all together in a synchronized way. They may interact by Compton effect with a Maxwellian electron distribution. These interactions are simulated using standard Monte-Carlo methods. For a fixed heating rate in the hot phase, the temperature of the electron distribution is modified according to the Compton energy losses due to the interactions with the LP photons. Starting from an arbitrary radiation field and temperature the system evolves naturally toward equilibrium. Then, the escaping LP characteristics are used to build up the angle dependent spectrum from the hot phase until a satisfying photon statistics is achieved.

The assumed geometry for the two-phase system is that illustrated in Figure 1.

3 Model parameters and numerical method

Our model is then fully defined when 5 parameters are given:

- Thomson optical depth τ_T of the hot phase, defined along its radius.
- Covering factor C of the cold material. C is the surface ratio covered by the cold clouds to that of the sphere. For a photon escaping from the hot sphere, C represents the probability of entering into the cold medium.
- Density of the cold (homogeneous) material n (cm^{-3}).
- Hydrogen column density of the cold material N_H (cm^{-2}).
- Ionization parameter of the cold material ξ, defined as $\xi = 4\pi F_{bol}/n$, where F_{bol} is the integrated flux incident on the cold material surface.

We compute the escaping spectrum as follows: First, we use the non-linear Monte-Carlo code in order to get a first estimate of the high energy spectrum. The hot sphere is assumed to have an homogeneous density, it is however divided in 5 concentric shells in order to account for temperature gradients that are computed according to the local energy balance. When a

photon LP escapes the hot sphere, a random number η is drawn:
• if $\eta > C$ the LP photon truly escapes and its energy is used to build up the escaping spectrum.
• if $\eta < C$ the LP photon enters the cold material. Its energy is then reemitted at the sphere surface in the form of LP photons. Their energy and direction are drawn from the assumed angle dependent spectrum of the cold material. Note that the reprocessed photons may be either directed toward the hot sphere (i.e. reflected) either directed outward and escape the system (i.e. transmitted through the cold phase).
At this stage the cold medium spectrum is purely arbitrary (although it is better if it is similar to a real reprocessed spectrum). We then inject the resulting equilibrium hot-phase spectrum as input in the TITAN/NOAR codes. This provides an estimate of the ionization and temperature structure of the cold phase as well as the reprocessed spectrum. Then we use the TITAN/NOAR spectrum as the local spectrum of the cold material in the NLMC code to get a better estimate of the hot-phase spectrum, and so on. In general, convergence is achieved after 3-4 iterations.

4 Example results

Figure 2 shows the resulting spectra for C=0.3 and C=0.5. We plot spectra for $\xi = 300$ and $\xi = 3000$ as well spectra that are obtained with the usual treatment of reprocessing (i.e. blackbody spectrum + neutral reflection). The blackbody temperature was fixed at kT_r=10 eV so that the thermal spectrum peaks at similar energies as the TITAN/NOAR spectrum, all the other parameters being kept to the same values.

As can be seen on this figure, the spectra are softer for larger C. This is due to the increase of reprocessed cooling flux from the cold material at larger C which leads to a lower temperature in the hot-phase.

There are sensible differences. The shape of the reprocessed spectrum obviously differs. But the comptonised emission differs as well. In particular, its slope is much softer. Indeed the reprocessed spectrum obtained by the TITAN/NOAR calculation is much broader than a blackbody, more photons being reprocessed at higher energy. This affects the Compton cooling in the hot phase (which is lower) together with the shape of the comptonised spectrum which is harder also due to the relatively high energy of the seed photons. This effect is then amplified by the fact that the hard X-ray albedo is larger for a harder spectrum thus enhancing the fraction of the reflected/reprocessed photons at high energy. In addition, in the "blackbody" simulations, the total flux impinging on the cold material is reemitted toward the hot sphere (i.e. transmission through the cold medium is neglected). In contrast, in the TITAN/NOAR simulations, the transmitted flux represents about 15 % of the impinging luminosity, despite our choice of a relatively large hydrogen column density of the cold medium. This "loss" of soft photons certainly contributes to the resulting higher temperatures and harder spectra in the TITAN/NOAR case.

The hardening of the spectrum increases with ξ (compare the spectra for $\xi = 3000$ and $\xi = 300$). The strongly ionized material has indeed a larger X-ray albedo, and more photons are reprocessed at high energies. We note however that the differences between the blackbody + neutral reflection model and the realistic one appear to be important even at moderate $\xi \sim 300$. This suggests that a detailed treatment of reprocessing is indeed required for most observationally relevant cases.

5 Conclusions

We calculated the equilibrium spectra in the context of the two-phase models for the emission from Seyfert galaxies and black hole binaries. For the first time, we included a detailed treatment of reprocessing and ionization and thermal balance in the cold phase.

We showed that the resulting equilibrium and escaping spectra are significantly affected by the shape of the reprocessed spectrum. The resulting broad band spectrum differs widely from that obtained using the usual "blackbody + neutral reflection" approximation. In particular, even for low ionization parameters, our realistic treatment of reprocessing leads to higher hot-phase temperatures associated with harder X-ray spectra.

Acknowledgments

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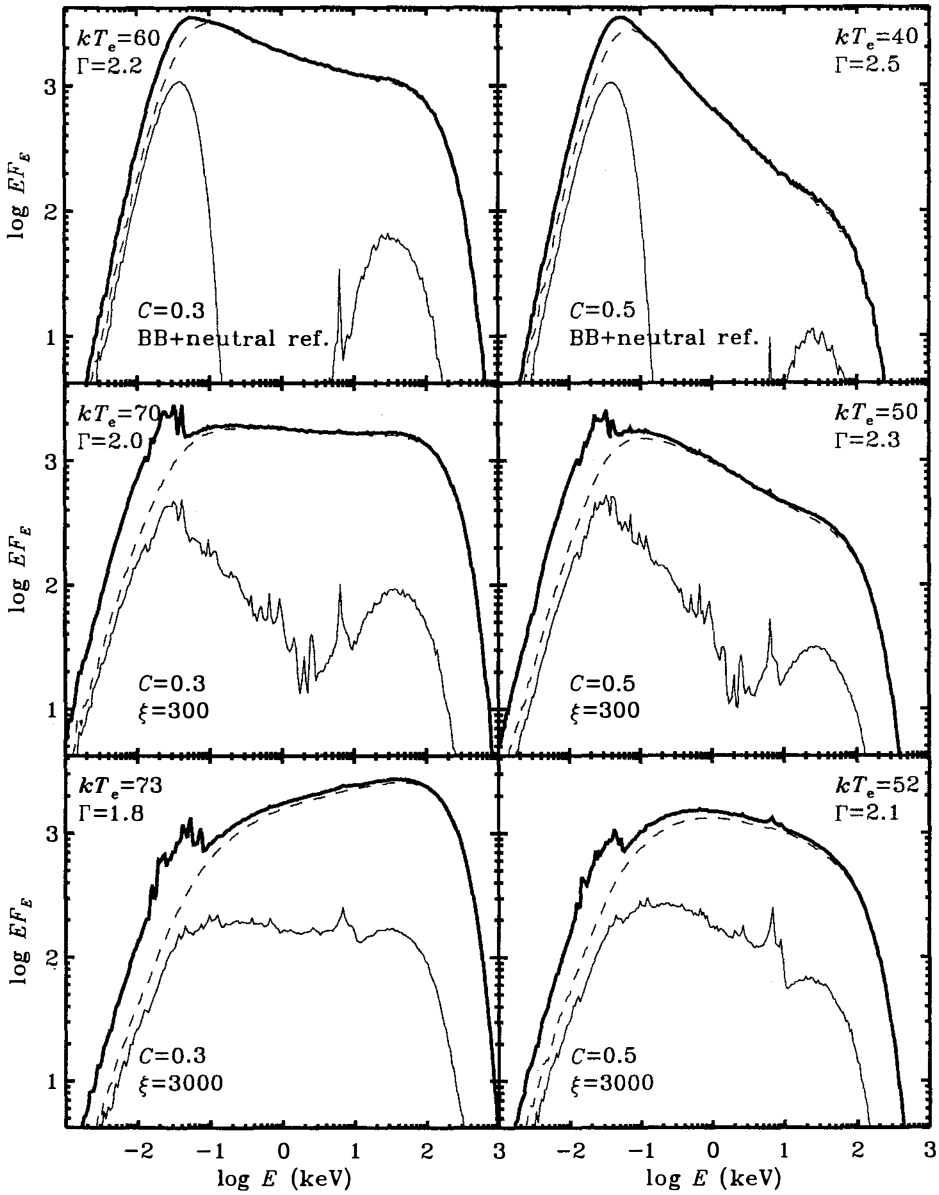

Figure 2: Escaping spectra for covering fractions $C = 0.3$ (left-hand side) and $C = 0.5$ (right-hand side). Thin curves: reprocessed/reflected spectrum. Dashes: Comptonised spectrum. Thick curves: total observed spectrum (including the transmitted component). The upper panels show the results from NLMC calculations with the cold phase emission approximated by a blackbody + neutral reflection. The blackbody temperature is kT_r=10 eV. The other panels are the results from the TITAN/NOAR/NLMC calculations for the following parameters of the cold medium: $n = 3\,10^{14}\,cm^{-3}$, $N_H = 3\,10^{25}\,\mathrm{cm}^{-2}$, $\tau_T = 1$. The assumed ionization parameter ξ is indicated in each panel together with the resulting 2-10 keV photon index Γ and the volume averaged temperature of the hot phase kT_e (in keV).