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Irradiated Accretion Disks from Galactic Black Holes to Active Galactic Nuclei

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Abstract This paper reports the status of the research on the effects of the irradiation of accretion disks. We cover both the X-ray spectra where the disk reflection is visible as well as the modifications of the optical/UV disk continuum. We discuss various geometries of the irradiation, including the photon scattering by the warm absorber and the disk corona which may be important for illuminating disk outer parts.

Key words: radiative transfer — accretion disks — galaxies:active — X-ray binaries

1 INTRODUCTION

The idea of accretion disks is around since many years. Optical observations made in 40' clearly indicated the presence of the streams of gas in close binaries (e.g. Struve 1949). A sketch of half of the ring with indication of an inflow from the ring towards the central star made by Walker & Herbig (1954) is one of the oldest pictures of an accretion disk in the literature. Theoretical effort made at the end of 60' and the beginning of 70' was motivated by the discovery of X-ray binaries (e.g. Prendergast & Burbidge 1968; Shakura 1972; Pringle & Rees 1972) and quasars (Lynden-Bell 1969). The classical model of disk accretion was established shortly afterwords by Shakura & Sunyaev (1973). Since that time the model was broadly recognized as frequently adequate description of the accretion flow in many objects, from Young Stellar Objects, through cataclysmic variables to X-ray binaries and active galactic nuclei.

Further development of the theory was initially hold back to some extent by the doubts concerning the accuracy of the parametrization of the viscosity in the classical model (see e.g. Pringle 1981) as well as the need for ad hoc model modifications in order to fit the data. The first problem was finally solved with the realization that magneto-rotational instability (Balbus & Hawley 1991) can account for the requested viscosity. The second problem is unsolved till now although various attempts were undertaken in order to incorporate additional physics into the description of the flow, going beyond the standard model. However, we are still far from the comfortable situation when the laws of physics tell us the properties of the flow. Separate effects are addressed by semi-empirical approaches made in confrontation with the observational data.

Here in this review we will concentrate on the irradiation effects on the accretion disks around black holes, either in binary systems (hereafter Galactic Black holes - GBH) or in active galactic nuclei (AGN).

2 STANDARD MODEL OF AN ACCRETION DISK

The standard model is the simplest model of an accretion disk. It is based on the following assumptions: the flow is stationary, the disk is geometrically thin but optically thick. In such case the knowledge of the viscosity and of the disk structure is actually unnecessary for determination of the accretion disk spectrum.

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The flux emitted by the disk surface at the radius r is given by the accretion rate, $\dot{M}$, and the depth of the potential well, i.e.

$$F(r) = \frac{3GM\dot{M}}{r^3}(1 - f(r)), \tag{1}$$

in the case of the Newtonian approach. Here M is the black hole mass and $f(r)$ (equal to $\sqrt{r_{\rm ms}/r}$) represents the inner boundary condition of vanishing torque at the marginally stable orbit $r_{\rm ms} = 3R_{\rm Schw}$, and the non-rotating black hole horizon is located $R_{\rm Schw} = 2GM/c^2$. This condition is modified if the accretion rate becomes comparable or larger than the Eddington rate (see Eq. (4)), as discussed by Paczyński & Bisnovatyi-Kogan (1981), Muchotrzeb & Paczyński (1982), Abramowicz et al. (1988), Afshordi & Paczyński (2003), if the magnetic field is exceptionally strong (Krolik 1999) or if the flow is optically thin (e.g. Chen et al. 1995) but in those cases the standard model does not apply.

The flux distribution determines the distribution of the effective temperature due to relation

$$F(r) = \sigma T_{\rm eff}^4, \tag{2}$$

where σ is the Boltzmann constant. This means that the effective temperature is zero at the inner, marginally stable radius, reaches the maximum relatively close to a black hole (at $\sim 4.8R_{\rm Schw}$) and falls down with the radius as $r^{-3/4}$. If the local emission is approximated by the Planck function, we can integrate the emission at a given frequency over the disk surface thus obtaining

$$F(\nu) \propto \nu^{1/3}(\dot{M}M)^{2/3} f(\nu), \tag{3}$$

so at low frequencies the spectrum is of a power law shape with the index 1/3 and the function $f(\nu)$ describes the roughly exponential drop at the frequency corresponding to a maximum emission a black body with the maximum temperature in the disk.

The main difference between the disks in GBH and in AGN lies in the position of the temperature maximum. For the same accretion rate in Eddington units, the disks in AGN have the temperatures two orders of magnitude lower, so the GBH disks emit frequently in X-ray band while AGN disks emit predominantly in UV. AGN disks are also much less ionized.

Any departure from the standard model requires either the knowledge of the disk structure, including viscosity, or arbitrary parametrization of the effect, or both.

3 APPLICATIONS OF THE STANDARD MODEL TO OBSERVATIONAL DATA

Considering the effect of irradiation is meaningful only if the standard model at least roughly applies to the description of the accretion flow. It is widely believed now that this is the case for moderate accretion rates, although the exact meaning of 'moderate' is under discussion. The reference is provided by the Eddington accretion rate:

$$\dot{M}_{\rm Edd} = \frac{4\pi GMm_p}{c\sigma_{\rm T}\eta}, \tag{4}$$

where $\eta = 1/12$ is the efficiency of accretion in Newtonian approximation and $\sigma_{\rm T}$ is the Thomson cross-section. The Eddington rate is the ratio of the object luminosity to the Eddington luminosity, or the accretion rate to the Eddington accretion rate. The standard disk model is widely considered to apply for $\dot{M}/\dot{M}_{\rm Edd}$ ratio from ~ 0.05 to ~ 0.5.

The spectrum predicted by standard model provides a nice representation of the observed spectra in the case of blue quasar composite of Richards et al. (2003) from SDSS, as illustrated by Czerny et al. (2004), as well as in the case of bright quasar composite of Francis et al. (1991), as shown by Koratkar & Blaes (1999). It is also a good model for GBH in their extreme soft states (see e.g. the softest state of XTE J1510–564 among those shown by Kubota & Makishima 2004).

Generally, the objects which are in the soft state (like GBH in the soft/high state and in the very high/intermediate states; AGN in their quasar or Narrow Line Seyfert 1 galaxy states) the classical disk component is clearly present but it does not explain the whole broad band spectrum well so some modifications of the model are needed. There seems to be a range of accretion rates when the required modifications are minor, with the departure increasing both with the rise of the accretion rate (see e.g. Kawaguchi 2003;

Kubota & Makishima 2004; Poutanen et al. 2007; Bonning et al. 2007) as well as with the drop, when there is a transition to the hard state, when the presence of the disk is hardly recognized (e.g. a review of Zdziarski & Gierliński 2004; Czerny 2003). In the case of AGN this transition is less clear, for example it is still under discussion whether Seyfert 1 galaxies are analogues of hard states or not, but in the case of very low accretion rates like in Sgr A* the presence of a cold accretion disk is ruled out by the lack of eclipses of the circumnuclear stars (Cuadra, Nayakshin & Sunyaev 2003). The generally accepted interpretation is that the cold disk forms at a fraction of the Eddington accretion rate, but for higher (super-Eddington) rate the advection effect turns in (the disk remains optically thick for scattering while becoming effectively optically thin for absorption, see Artemova et al. 2001, 2006) while at lower accretion rate the disk in the inner part evaporates (e.g. Różańska & Czerny 2000; Meyer, Liu & Meyer-Hofmeister 2000) and the cold accretion disk is replaced with a hot optically thin flow, again with a significant effect of advection (Ichimaru 1977, Narayan & Yi 1994). How exactly this process proceeds, and at what value of the accretion rate, is a matter of debate (see e.g. Dullemond & Spruit 2005; Nakamura 2007; Meyer, Liu & Meyer-Hofmeister 2007; Yuan et al. 2007).

3.1 Departures from the Standard Model and Alternatives

The observed spectra have to be corrected for the Galactic absorption and the starlight component (either circumnuclear stars in AGN or a companion in a binary) before comparing with the classical disk. For quasars this contribution is small but may not always be totally negligible. In some sources there is a huge internal extinction along the line of sight (an extreme example being Compton-thick Seyfert 2 objects) and in those cases the detection of the disk is very difficult. For disk model tests, relatively unobscured objects should be selected.

Even in the case of intermediate accretion rates the standard disk is not a perfect model. Its atmosphere emission shows departures from the black body (Shakura & Sunyaev 1973; Czerny & Elvis 1987; Hubeny et al. 2000; for a recent review see Blaes 2007). This effect is mostly due the electron scattering and Comptonization, which are particularly important if there is some heat dissipation in the atmospheric layers due to magnetic field reconnections.

There are numerous works which supplement the standard model with additional spectral components:

- an IR-X-ray power law (e.g. Malkan & Sargent 1982) representing the possible jet contribution
- X-ray power law or more advanced models of Comptonization, representing the inner hot flow or the disk corona.

The components related to the X-ray reprocessing will be discussed later on. Some authors suggested a different geometry of accretion flow. Quasi-spherical accretion of clumpy material was proposed, with magnetically confined optically thick clouds (Guilbert & Rees 1988; Lightman & White 1988) or with less dense clouds of moderate optical depth (Collin-Souffrin et al. 1996). This kind of models also found their application in AGN data analysis (e.g. Goosmann et al. 2007; Longinotti et al. 2007). It is not likely that the flow is indeed spherical but the element of clumpiness probably reflects the aspect of the possible clumpiness of the flow, usually ignored in the disk models.

Later in this review we will concentrate on objects to which the classical disk model roughly applies and we will discuss the effects imposed on the disks by irradiation.

4 IRRADIATION OF ACCRETION DISKS

The effects of the disk irradiation can be conveniently divided into two parts: the modification of the spectrum at energies higher than the peak of the standard model and below it. Typically this will coincide with the division to X-ray part and the optical/UV part of the spectrum, accordingly.

4.1 X-ray Irradiation and X-ray Disk Reflection

If there is a hot plasma located somewhere above the disk which is the source of the X-ray emission then the disk classical spectrum is supplemented with the primary emission, and the disk emission is modified by the incident X-ray photons which leads to the presence of the so called ‘reflected component’. This reflected component forms due to scattering of the primary photons as well as due to the re-emission of the absorbed radiation and it consists of the Compton hump and X-ray emission lines (of iron and other elements). Narrow lines emitted locally are smeared due to general relativistic effects leading to formation of a broadened lines. The basic idea of X-ray reflection was formed by Lightman & White (1988), and the component was firmly seen for the first time in the Ginga composite spectrum (Pounds et al. 1990).

There was a considerable progress in this area during the recent years since the relativistically broadened emission lines are at present the best probes of the innermost region of accretion flow (see Fabian 2007 for a review). The work was done with respect to local description of the reprocessing, accuracy of the description of relativistic effects, geometry and motion of the hot emitter and the spectral variability.

4.1.1 Local Reprocessing

Initial considerations of the X-ray reprocessing were based on the assumption that the density of the reprocessing medium (disk) is constant and the medium is neutral (Lightman & White 1988). Later the effects of the partial ionization of the medium were included, and the ionization level was calculated self-consistently from the ionization/recombination balance (e.g. Życki et al. 1994; Życki & Czerny 1994). However, the density of the disk atmosphere is not constant but varies dramatically with the optical depth, and the density profile is roughly determined by the condition of the hydrostatic equilibrium. It does not only mean that the variable density has to be taken into account but it implies that we usually deal with the thermal instability (Krolik, McKee & Tarter 1981). This instability leads to the presence of discontinuity in the density distribution of an irradiated disk (Begelman, McKee & Shields 1983) thus dividing the disk atmosphere into the Compton-heated hot corona and lower atmosphere zone cooled by atomic processes. In the outer parts of the disk, when the disk surface gravity is low the Inverse Compton corona is gravitationally unbound and the static corona is replaced by the wind solution.

The models of the irradiated disk spectra with hydrostatic equilibrium were first presented by Nayakshin, Kazanas & Kallman (2000) and later developed e.g. by Różańska et al. (2002), Collin et al. (2003) using independent numerical codes. There were also attempts to incorporate the turbulent structure of the disk surface layers (e.g. Ballantyne et al. 2005), and the recent numerical simulations of the disk surface layers (Blaes, Hirose & Krolik 2007) indicate that the effect is likely to be important.

4.1.2 Relativistic Effects

The initial estimates of the shape of relativistically smeared iron line were done by Fabian et al. (1989), and in many later applications the XSPEC routine of Laor (1991) was adopted. The relativistic smearing of the Compton hump was already considered by Życki, Done & Smith (1997). Recently a new program (Dovciak, Karas & Yaqoob 2004) was implemented into the standard XSPEC software which is fast and gives considerable flexibility in the modeling of the the relativistic smearing of the reflected spectra. In some papers the effect of the relativistic smearing was already calculated for a relatively accurate local reflection spectrum, with all the lines and reflection hump automatically included (e.g. Goosmann et al. 2006).

4.1.3 Geometry and Motion of the Emitter

The geometry and location of the emitter of primary radiation is the main unsolved problem of the innermost part of accretion flow. Therefore, a parametric description is always adopted and later the predicted models are compared to the observational data. The popular model is lamp post geometry (a single source of X-rays located at the symmetry axis) motivated by the physical model of jet basis emitter (Henri & Pelletier 1991). Such a geometry was used by Różańska et al. (2002). If the source is located close to a black hole horizon then the light bending of the incident radiation becomes important (Miniutti & Fabian 2004). The reflection also changes if the emitter has a significant velocity with respect to the disk surface (Beloborodov 1999): the reflection is enhanced if the hot plasma flows towards the disk and suppressed if the hot plasma flows away. If the primary emission is due to many magnetic flares above the disk the reflection is a combined effect of the many hot spots localized at the disk surface. Since the relativistic smearing effects depend on the spot location the X-ray spectrum in principle allows for localization of the emission (e.g. Goosmann et al., in preparation). However, with present instruments this is almost impossible apart from the rare cases of the exceptionally bright long-lived flare (e.g. Tombesi et al. 2007).

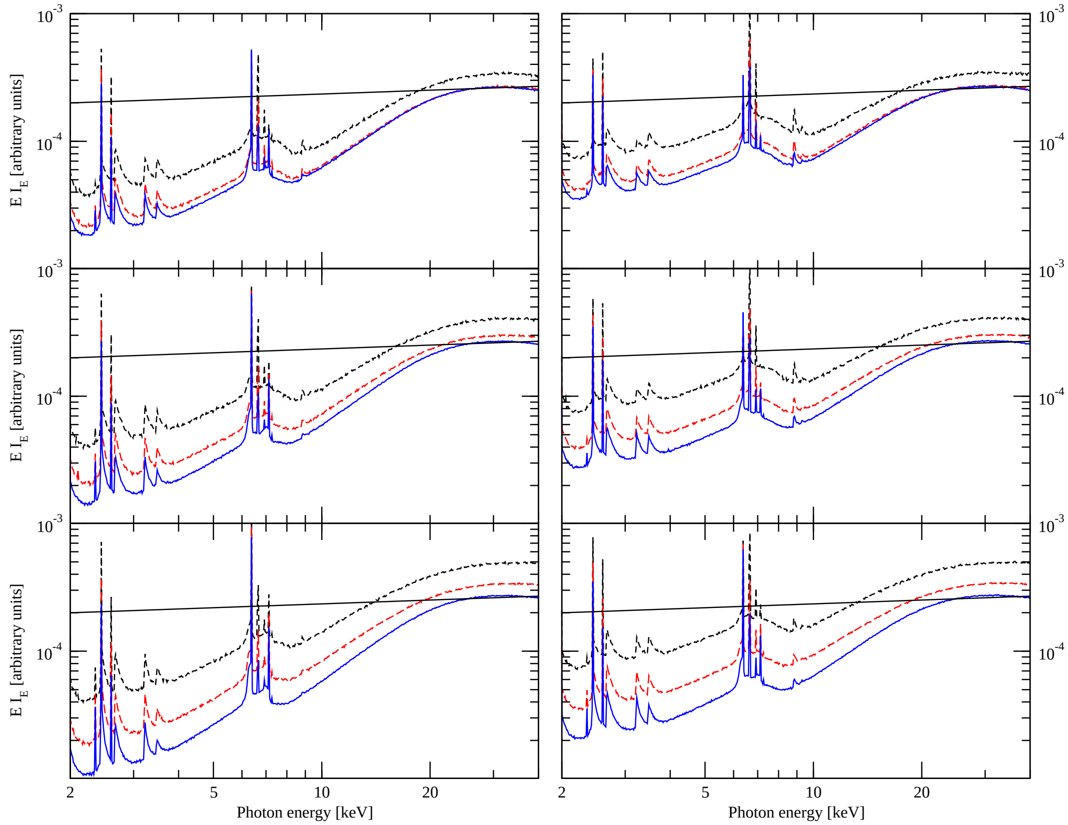

Fig. 1 Example of the reflection in a model taking into account both the vertical stratification of the medium as well as the dependence of the spectrum from the distance from the spot center located directly underneath the magnetic flare. Left column: flare at 3.5 $R_{\rm Schw}$, right column flare at 9 $R_{\rm Schw}$; upper panels: innermost part of a spot, middle panels: intermediate part of the spot, lower panels: outer coolest parts of the hot spot. Each panel shows three lines for three values of the viewing angles: 20° (upper line), 60° (middle line) and 80° (lower line); Goosman et al., in preparation

4.1.4 Variability of the Reflection Component

The strong variability of the primary emission was expected to lead to a correlated variability of the reflected component. The initial search did not confirm this expectation (Reynolds 2000). Most analysis done both in the context of AGN and GBH rather suggested a constant level of reflection, seen for example as a depression in the variability level at energies corresponding to the position of the iron line (e.g. Markowitz, Edelson & Vaughan 2003), particularly at high Fourier frequencies in Fourier-resolved analysis (e.g. Revnivtsev, Gilfanov & Churazov 2001; Papadakis, Ioannou & Kazanas 2007). However, occasional variability of the reflection was seen (e.g. Miller et al. 2006). The apparent suppression of the variability at some energies is expected both in the case of light-bending model (Miniutti & Fabian 2004 but see Życki & Niedzwiecki 2006 and Thomas Boller, this Proceedings) as well as in the case of multi-flare model (Goosmann et al. 2006).

4.2 Effects of the Disk Irradiation in the Opt/UV Band

The effects of irradiation at low energies are even more complex. First of all, we have now two sources of the irradiating flux: X-ray irradiation discussed before and irradiation of the outer parts of the disk by the inner parts, radiating more efficiently.

X-ray irradiation leads not only to reflection but also to thermalization of the fraction of the incident flux. The ratio depends on albedo which is about 0.2 for almost neutral gas and drops to 0.5 for significantly ionized medium. The thermalized flux increases the disk temperature. Some of the local models of the reprocessing include the computation of the emission of this component and the resulting disk spectrum consists of a quasi-black body peak in optical or UV and the reflected X-ray component (e.g. Różańska et al. 2002).

Irradiation of the disk outer parts by UV emission also leads to absorption of the incident radiation with even larger efficiency.

The effect of the irradiation consists both of the modification of the disk continuum as well as the formation of emission lines (Collin-Souffrin 1991). The emission lines in optical/UV is a very complex issue, particularly in the context of AGN, and this subject itself would require a separate review. It is only worth to mention that Low Ionization Lines (like Hβ or MgII) are likely to form in the accretion disk atmosphere (Collin-Souffrin et al. 1988) while High Ionization Lines (like CIV) probably form in a disk wind. In the present review we will concentrate on the disk continuum emission.

4.2.1 Modification of the Local Disk Spectrum due to Irradiation

Advanced disk spectra going beyond the standard model were obtained either by more accurate radiative transfer computations without irradiation effect (e.g. Hubeny et al. 2000; Davis, Done & Blaes 2006) or by simple addition of the incident radiation flux thus modifying the effective temperature but still keeping the assumption of the local black body emission (e.g. Soria & Puchnarewicz 2002). The progress was hold back by the fact that more advanced models predicted the formation of the Lyman and Balmer edge while such a feature was not seen in the observational data. The latest observational work on quasar spectra (Shang et al. 2005) roughly reconciles the data with the advanced models. The traces of the expected Balmer edge in quasar spectra were also finally found although only in the polarized light (Kishimoto et al. 2004).

4.2.2 Geometry of the Irradiation Process in opt/UV

When we concentrate on the optical part of the spectrum it is clear that the corresponding temperature is low and the emission comes from the distant disk radii, particularly in the case of GBH. Since the inner disk emission and the X-ray emission are concentrated in the innermost part of the disk there is a question how the irradiating photons reach the disk outer parts. From this point of view, independently on the photon source, we can consider three options:

– direct irradiation
– scattering by the disk corona
– scattering by the warm absorber/wind

All three effects are possibly present.

The direct irradiation is probably more important in the case of the GBH disks since the height to the radius ratio is higher for those disks at the same Eddington ratio (e.g. Loska, Czerny & Szczerba 2004). The effect was discussed for GBH and AGN by numerous authors, for example Collin-Souffrin (1991), King (1998) (see Loska et al. for more references). Wu et al. (2001) give a nice observational evidence for a strong irradiation in the case of GX339-4 in its soft state.

The scattering by the hot fully ionized corona was considered by Ostriker, McKee & Klein (1991). Since the formation of the Compton-heated corona depends on the local disk irradiation and the local disk irradiation depends on the coronal geometrical height, a complex self-consistent models of this process were developed (e.g. Murray et al. 1994; Esin et al. 1997). The comparison of the line ratios and line profiles with the data within the frame of such a model was quite successful (Kurpiewski et al. 1997) but not much work was done along this line.

The scattering by the (almost) fully ionized warm absorber was suggested by Loska et al. (2004). The idea was motivated by the possibly large column density of the warm absorbers in Narrow Line Seyfert 1 galaxies claimed by King & Pounds (2003). Since the X-ray data are only sensitive to the absorption, and not to scattering, by the warm absorber, the study of the spectrum modification in the optical/UV part offers much better possibility to constraint the optical depth of the fully ionized fraction of the outflow. If the column density of the warm absorber is of order of a few time 10^{23} cm^{-2} or higher then the effect in the optical/UV band is clearly seen. However, it is quite difficult to differentiate between the coronal scattering and the warm absorber scattering at the basis of the spectra alone (Czerny & Janiuk 2007).

4.2.3 Time Delays

Time delays of order of a day between the various continuum opt/UV continuum bands were measured in a number of Seyfert galaxies (e.g. Sergeev et al. 2005). Such delays are roughly consistent with the scenario of the variable irradiation. We recently used the delays measured for Mkr 335 to test the irradiation scenarios (Czerny & Janiuk 2007). Expected delays are longer in the warm absorber scenario and shorter in the disk corona scenario. Only the second model was consistent with observational data, if the mass of the central object had to be consistent with the black hole mass measurements based on reverberation. It might indicate that strong optically almost thick warm absorber outflow postulated by King & Pounds (2003) and later discussed by Gierliński & Done (2006) or Done et al. (2007) is not likely to be acceptable for this source. The model should be similarly tested for other sources but for most monitored sources there are no reliable mass measurements an independent X-ray determination of the warm absorber properties, and other sources were not monitored for short term variability.

4.3 Evolutionary Effects Caused by Irradiation

Evolutionary effects can be much easier studied in the case of GBH since the timescales in a given object (months — years) are directly within the accessible range for observational tests. GBH sources show outbursts referred as X-ray novae which are caused by the ionization instability in the outer part of the disk. The same instability works in the cataclysmic variables (CV). However, although the accretion rates in those disks are similar, and the mechanism the same, there are clear differences between the outbursts in those two classes of sources. In CV the outbursts are symmetric, and more frequent while in GBH the Outbursts frequently show the fast rise (as in CV) but slow exponential decay lasting a hundred days instead of a few. King (1998) suggested that this effect is caused by a strong irradiation of an outer disk in GBH while no such strong irradiation is possible in CV with a white dwarf as a central object and much cooler inner disk. Irradiation enhanced the flow and prolongs the outburst by preventing the transition of the disk into the cooler weakly ionized phase.

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DISCUSSION

FILIPPO FRONTERA: In general the bump around 10–20 keV is interpreted as due to the Compton reflection from the disk. But the disk, especially the inner disk, is likely to be ionized. In this case, another interpretation of the bump is possible - of Titarchuk et al. - as due to a redshifted annihilation line. Can you comment this possibility?

BOŻENA CZERNY: It is a question of good observational data. The Compton hump predicted by the reflection has a specific shape. Its low energy tail (the amount of bending towards 10 keV) depends on the ionization state but the high energy part does not. If the observational data favors this shape then I would think that other models are unlikely since they would require a very specific interplay between the photon escape probability and photon emissivity as a function of radius to mimic the requested shape. The problem is that I am not sure how accurately the shape of the hump is determined by the Beppo-Sax and Suzaku data.