Irradiation of accretion discs in active galactic nuclei due to warm absorber

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ABSTRACT
The presence of the warm absorber of considerable optical depth is seen in many AGN. We show that this medium may affect significantly the optical/UV spectrum of an AGN by backscattering a fraction of the total radiation flux towards the disc surface. We consider in detail the case when the disk extends down to a marginally stable orbit, all the emission comes from the disk surface and the scattering medium forms a cone around the symmetry axis. Disc irradiation results in much flatter optical/UV continuum than predicted by standard disc models. The effect depends both on the total optical depth of the warm absorber and on the specific density distribution of this medium so the analysis of the optical/UV continuum allows to obtain constraints for the warm absorber complementary to those obtained from the soft X-ray data analysis. We give results for two exemplary sources - RE J1034+396 and PG1211+143, and for the bluest composite quasar spectrum of Richards et al. obtained from SDSS.

Key words: Radiative transfer, Accretion discs, Galaxies:active, Galaxies:Seyfert, X-rays:galaxies

1 INTRODUCTION
Optical/UV spectra of bright active galactic nuclei (AGN) are usually interpreted as originating from an accretion disc surrounding the central massive black hole (Lynden-Bell 1969, Shields 1978, Malkan & Sargent 1982; for a review, see e.g. Koratkar & Blaes 1999, Czerny 2003). However, both the shapes of the radiation spectra and the variability studies (e.g. Wanders et al. 1997, Collier et al. 1998 for NGC 7469; see Ulrich, Maraschi & Urry 1997 for a review) suggest that significant fraction of radiation emitted at a given radius is due to the reprocessing of the radiation dissipated elsewhere.

Most of the radiation is produced in the deep potential well, close to the black hole. In quasars and Seyfert 1 galaxies part of this radiation reaches an observer directly. However, part of the radiation may be recaptured by the outer disc region.

The irradiation of the disc may be direct or indirect. In the first case the disc must be exposed to the radiation flux generated in the inner region. In the second case there may be a scattering medium which redirects a part of the radiation back towards the disc.

The direct irradiation of AGN accretion discs was discussed by several authors (e.g. Krolik et al. 1991, Courvoisier & Clavel 1991, Collin-Souffrin 1991, Rokaki et al. 1993, Loska & Czerny 1997, Kurpiewski et al. 1997, Sincell & Krolik 1997, Collin & Huré 1999, Nayakshin et al. 2000, Ballantyne et al. 2001, Nayakshin & Kazanas 2002, Soria & Puchnarewicz 2002, Różańska et al. 2002, Chiang & Blaes 2001, 2003, Chiang 2002). Most of these papers were actually devoted to the irradiation of the inner disc by the hard X-rays generated in a lamp-post or disc corona. Much of the research had been done in the context of X-ray binaries (e.g. Raymond 1993, Dubus et al. 2001, Jimenez-Garate et al. 2002) or cataclysmic variables (Meyer & Meyer-Hofmeister 1982, Smak 1989) and the methods are directly applicable to AGN discs but the results may not apply quantitatively since the disc shape depends on the mass of the central object, as already seen from the classical paper of Shakura & Sunyaev (1973).

The indirect irradiation was also considered in several papers (Ostriker et al. 1991, Murray et al. 1994, Kurpiewski et al. 1997; also Esin et al. 1997 in the case of galactic sources). These authors analyzed the scattering of the radiation in the accretion disc corona.

In the present paper we consider the scattering of the disc radiation by the warm absorber. The warm absorber medium, seen in many AGN (for a review, see e.g. Kriss 2004), is a highly ionized plasma so it predominantly scatters the passing radiation, with absorption important only in the soft X-ray band. The optical depth of the warm absorber for scattering is difficult to measure but estimated values can be as high as 0.33 or more for PG1211+143 (Pounds
et al. 2003a), 0.26 or more for PG PG 0844+349(Pounds et al. 2003b), 0.20 or more for PG 1402+261 (Reeves, Porquet & Turner 2004). Arav et al. (2003) show by analyzing OVI UV absorption and OVI X-ray absorption in NGC 5548 that simple modelling gives discrepant results and in general heavily underestimates the amount of outflowing material.

Therefore, a significant fraction of the radiation flux emitted by the central region can be in such way redirected towards the outer parts of the accretion disc and thermalized there. Therefore, the presence of highly ionized warm absorber of considerable optical depth must modify the IR/optical/UV disc spectra. We can apply this effect either to explain the departure of the observed spectrum from the simple prediction of the accretion disc model or, if no such clear departure is seen, as an independent way to put limits to the optical depth and the covering factor of the warm absorber.

The effect should be present in all AGN, but it is potentially most important when the direct disc irradiation by an X-ray source is relatively weak. We assume the accretion flow proceeds through a standard disc which extends down to the marginally stable orbit. We neglect any hard X-ray emission. We calculate the optical/UV spectra of the accretion discs taking into account the scattering of the disc flux by the warm absorber as well as the effect of the direct self-irradiation of the disc.

As an application, we show the spectra models for two NLS1: RE J1034+396 and PG 1211+143, and for the composite 1 quasar spectrum of Richards et al. (2003).

2 METHOD

We consider the self-irradiation of the disc both due to direct self-illumination and due to radiation scattering by the warm absorber.

In the case of an extended scattering medium, there is practically no dependence of the result on the disc shape. However, the direct irradiation is very sensitive to the adopted disc shape: the disc must flaring in order to have its surface exposed to the central source. We must specify the disc model appropriate for an AGN in order to see which disc parts actually are irradiated.

Therefore, in Sect. 2.1 we describe the disc model, in Sect. 2.2 we describe the formulae for the direct irradiation, in Sect. 2.3 we describe the warm absorber model and the method of computing the incident flux at a given disc radius, and in Sect. 2.4 we describe the method of calculating disc spectrum.

2.1 Disc shape

We use the stationary Keplerian disc model of Różańska et al. (1999). The disc thickness is calculated by solving the equations of the disc vertical structure. Viscosity is described assuming the standard $\alpha$ approach of Shakura & Sunyaev (1973), i.e. we assume that the viscous torque is proportional to the total (gas + radiation) pressure. Recent studies of magneto-rotational instability generally supports the validity of such scaling (e.g. Turner 2004). Estimates based on the MHD simulations of the MRI instability indicate the average value of the effective viscosity parameter $\alpha$ about 0.02 (Winters et al. 2003), and similar values of $\alpha$ between 0.01 and 0.03 were derived from the analysis of the AGN variability (Starling et al. 2004).

The disc vertical structure (as a function of the distance $z$ from the disc equatorial plane) is calculated by solving the equations of viscous energy dissipation, hydrostatic equilibrium, and energy transfer:

$$\frac{dF}{dz} = \alpha P_{\text{rad}} \left( -\frac{d\Omega}{dz} \right)$$

$$\frac{1}{\rho} \frac{d\rho}{dz} = -\Omega^2 z$$

$$\frac{dT}{dz} = -\frac{3k\rho}{c_s^2 T^3} F_1.$$  

Here $\Omega$ is the Keplerian angular velocity, $c_s$ and $c$ are physical constants. $F_1$ is the energy flux transported locally in the direction perpendicular to the equatorial plane and carried either by radiation or by convection:

$$F_1 = F_{\text{rad}} \quad \nabla_{\text{ad}} \leq \nabla_{\text{rad}}$$

$$F_1 = F_{\text{rad}} + F_{\text{conv}} \quad \nabla_{\text{rad}} > \nabla_{\text{ad}}$$

These equations, supplemented by the equation of state, describe the temperature, density and pressure profiles, $T(z)$, $\rho(z)$ and $P(z)$.

The frequency-averaged opacity $\kappa$ is taken to be the Rosseland mean and includes the electron scattering, free-free and bound-free transitions. The opacity tables are from Alexander, Johnson & Rypma (1993) and Seaton et al. (1994). The presence of dust and molecules is included in the opacity description. The details of the model were discussed in Pajmński 1988 and Różańska et al. (1999).

Disc thickness is determined iteratively, from the condition that the energy flux dissipated inside the disc is equal to the energy flux given by assumed accretion rate through the standard formula

$$F(H, r) = \frac{3GM\dot{m}}{8\pi r^3} \left( 1 - \sqrt{\frac{r}{3R_{\text{Schw}}}} \right) + F_{\text{inc}}(H, r)(1 - A).$$

This means that we use the Newtonian approximation for a non-rotating black hole. Consequently, we use the dimensionless accretion rate in Eddington units, $\dot{m} = \dot{M}/\dot{M}_{\text{Edd}}$, with the efficiency of 1/12:

$$\dot{M}_{\text{Edd}} = 2.66 \frac{M}{10^6 M_\odot} [M_\odot/\text{yr}].$$

The effect of irradiation is included only through the additional term present in Eq. 5 (see e.g. Tuchman et al. 1990), where $F_{\text{inc}}$ is either $F_{\text{direct}}$ or $F_{\text{inc}}$, or both, since we concentrate on the overall spectral shape, particularly in the optical/UV band. This term describes the absorbed fraction of the external incident flux. The method of determination of this flux is described in the Sections 2.2 and 2.3. The albedo, $A$, is assumed to be independent from the photon energy and its energy-independent mean value is assumed to be equal to 0.2, appropriate for cold disc surface (see e.g. Haardt & Maraschi 1991).

2.2 Direct irradiation

Computing the direct irradiation we follow the approach of Fukue (1992).
The incident flux at a given disc radius, $r$, the integral over the disc surface thickness at the radius scattering by the warm absorber was suggested by Czerny et al. (2003). It could be seen from Fig. 3 of this paper that the warm absorber absorbs efficiently only in the soft X-ray band while for lower frequency photons the opacity is equal to that of electron scattering and this effect dominates the overall extinction in the optical/UV band. The key parameter is the ionization parameter $\xi$ defined as

$$\xi = \frac{L}{nR^2},$$

where $L$ is the luminosity of the central source, $n$ is the number density of the shell and $R$ is the inner radius of the shell.

We calculated the irradiation flux from the given distribution of the emitted flux, $F_{em}(r)$ and the disc shape, $H(r)$. The incident flux at a given disc radius, $r_o$, has the form of the integral over the disc surface

$$F_{direct}(r_o) = \frac{4}{\sqrt{1 + (\frac{4H_o}{D_s})^2}} \int_0^{\pi} \int_{R_{in}}^{R_{out}} F(H, r) \cos i \cos i_o \sqrt{1 + (\frac{4H_o}{D_s})^2} r dr d\phi,$$

(7)

with an additional condition that the contribution to the integral is included only if

$$\cos i > 0, \quad \cos i_o > 0.$$

(8)

The incident flux $F_{inc} = F_{direct}$ is calculated at the radius $r_o$, $r$ is the current radius of integration over the disc surface, $H_o$ is the disc thickness at $r_o$, while $H$ is the disc thickness at the radius $r$, $i_o$ and $i$ are the corresponding angles between the normal to the disc surface and the line joining two disc surface points, as marked schematically in Fig. 1. The distance $D_s$ between the irradiating and irradiated surface element is given by

$$D_s^2 = r^2 + r_o^2 + (H - H_o)^2 - 2rr_o \cos \phi,$$

(9)

the angle $i$ is determined by

$$\cos i = \frac{\frac{4H}{r} \cos \phi + H_o - H}{D_s \sqrt{1 + (\frac{4H_o}{D_s})^2}},$$

(10)

and the angle $i_o$ is determined by

$$\cos i_o = \frac{\frac{4H}{r_o} \cos \phi + H - H_o}{D_s \sqrt{1 + (\frac{4H_o}{D_s})^2}},$$

(11)

Radiation flux from the disc is determined by the Eq. (5). Since the effect of irradiation depends on the shape of the disc, and both the disc shape and the local emissivity depend on irradiation, the result is obtained through consecutive iterations, starting from unilluminated disc. Usually 2 - 3 iterations are enough to provide the result with the accuracy better than 1%.

### 2.3 Scattering by the warm absorber

The idea of redirecting some of the disc radiation flux emitted in the central region towards the outer part through scattering by the warm absorber was suggested by Czerny et al. (2003). It could be seen from Fig. 3 of this paper that the warm absorber absorbs efficiently only in the soft X-ray band while for lower frequency photons the opacity is equal to that of electron scattering and this effect dominates the overall extinction in the optical/UV band. The key parameter is the ionization parameter $\xi$ defined as

$$\xi = \frac{L}{nR^2},$$

where $L$ is the luminosity of the central source, $n$ is the number density of the shell and $R$ is the inner radius of the shell.

We checked the effect using the code CLOUDY, version 94.0, for a spherical shell geometry. The reflected continuum is redirected towards the disk and the transmitted continuum is seen by an observer. For $\xi = 10^4$ the warm absorber imprints significant features in the X-ray band into the transmitted spectrum which allow to determine the hydrogen column of the absorbing medium. Narrow absorption lines form also in the UV band. At the same time the overall reflected spectrum still is not much different from the intrinsic continuum. In the case of almost fully ionized absorber ($\xi = 10^5$) electron scattering dominates so strongly that actually almost no spectral features are seen. It supports even better our later approach based on the negligence of absorption processes. At the same time, it illustrates potential problems in detecting warm absorbers. An extremely strongly ionized medium with large optical depth may well exist in an object and still escape detection by analysis of the soft X-ray data.

The presence of the dust within the warm absorber complicates the issue. As an example, we considered a case with $\xi = 10^5$, but we allowed for an additional fraction of dust, at amount of 1% of the standard gas to dust ratio for the interstellar medium in our Galaxy, and of the same composition. Electron scattering is still quite effective, and the dust also partially scatters the incident photons. The net effect is strong reddening in the transmitted continuum and relatively minor suppression of the UV part in the reflected spectrum. Details of those effects depend significantly on the dust composition. The possible presence of the dust in the warm absorber is discussed in a number of papers (e.g. Koss & Breitschwerdt 2000, Mason et al. 2003, Ballantyne, Weingartner & Murray 2003).

In the present paper we concentrate on objects which are not heavily reddened in UV and we consider the warm absorber medium as purely scattering fully ionized plasma.

The origin, the geometry and the physical state of the warm absorber are still under discussion. As for the source of material, ideas include accretion disk winds/Broad Line Region clouds (Elvis 2000, Kriss et al. 2003, Blustin et al. 2003), inner edge of the dusty/molecular torus (Krollik & Kriss 2001) and radiation driven clouds constituting the Narrow Line Region (Crenshaw et al. 2000). King & Pounds (2003) go as far as suggesting that actually the outflow from the direct vicinity of an accreting black hole can be strong enough to form an optically thick shell that Comptonize the emission from the directly unseen inner source.

Narrow absorption lines in many spectra of Seyfert 1 galaxies indicated a clumpy medium with numerous colder clumps embedded in an fully ionized hotter medium (Crenshaw et al. 1999; Kriss 2002; Krolik & Kriss 2001, Blustin et
al. 2003) while 280 ksec XMM-Newton spectroscopy of NGC 3783 (Behar et al. 2003) suggested mostly uniform medium, at distances up to 2.8 pc from the nucleus.

The optical depth of the warm absorber is poorly constrained since the directly measured column density of specific ions must be supplemented with modelling of the ionization state of the plasma in order to obtain the hydrogen column.

If cooler clumps are embedded in a fully ionized medium the contribution of this medium is particularly difficult to estimate while it may significantly enhance the total optical depth of the medium for electron scattering.

Detection of the variability in the OVIII hydrogen column of MCG-6-30-15 (Otani et al. 1996) allowed to estimate the distance of the warm absorber as smaller than 10^{17} cm but the lack of variability in the OVII edge suggested that the warm absorber is rather spatially extended, with highly ionized flow closer in and less ionized flow further out, as visualized by Blustin et al. (2003). Models based on evaporation of the inner torus suggest distances of a fraction of a parsec while models with disk outflow suggest distances of a few Schwarzschild radii for fully ionized flow.

Radial velocities of warm absorber features of order of a few hundreds km/s determined in a number of sources, if interpreted as roughly Keplerian speed, may indicate rather large distances and the connection with dusty torus (e.g. Ashton et al. 2004). Large velocities claimed to be seen at distances up to 2.8 pc from the nucleus.

We assume that the warm absorber has an axially-symmetric conical shape. It extends from the inner radius, \( R_{min} \), to the outer radius, \( R_{max} \), with the opening angle of the cone given by \( \theta_{max} \). The schematic picture is shown in Fig. 2.

The density of the warm absorber depends on the radial distance from the center, \( R \) in the form

\[
n(R) = n_0 \left( \frac{R}{R_{min}} \right)^{-\beta},
\]

where the density at the inner edge of the warm absorber is conveniently expressed as

\[
n_0 = \frac{\tau_{tot}}{\sigma_T \int_{R_{min}}^{R_{max}} \left( \frac{R}{R_{min}} \right)^{-\beta} dR},
\]

since the total optical depth of the warm absorber, \( \tau_{tot} \), is relatively easily estimated from observations. We can also include in our scheme the dependence of the density distribution on \( \theta \).

Since the warm absorber is an extended medium, we neglect the extension of the inner parts of the disc where most of the energy is generated and we assume that the whole radiation comes from a point-like source. Its luminosity, \( L \), is determined by the accretion rate

\[
L = \dot{m} L_{Edd}.
\]

We take into account the finite optical depth of the warm absorber so the local emissivity of this medium due to the electron scattering is given by

\[
j(R, \theta) = \alpha_T(R) \frac{2L \cos \theta}{4\pi R^2 \exp[-\int_0^R \alpha_T(s) ds]},
\]

where the opacity \( \alpha_T \), is the Thompson opacity (\( \alpha_T(R) = \sigma_T n(R) \)).

This extended medium returns the fraction of the scattered radiation towards the disc. The resulting illumination is calculated as

\[
F_{sc}(r_o) = \frac{1}{4\pi} \int_0^{2\pi} \int_{R_{min}}^{R_{max}} \int_0^{\theta_{max}} \frac{j(R, \theta) R^2 \sin \theta \cos i_o}{D_w^2} d\theta dR d\phi,
\]

where

\[
\cos i_o = \frac{dH_w}{dr_o} (r_o - R \sin \theta \cos \phi) + R \cos \theta - H_w}{D_w \sqrt{1 + \left( \frac{dH_w}{dr_o} \right)^2},
\]

and

\[
D_w^2 = r_o^2 + R^2 + H_w^2 - 2R(r_o \sin \theta \cos \phi + H_w \cos \theta).
\]

### 2.4 Accretion disc spectrum

Accretion discs in high Eddington rate AGN are optically thick and they thermalize the absorbed radiation efficiently. The models of the emitted local spectrum, however, show some departure from the local black body approximation due to the role of the Compton scattering in the disc outer layers (e.g. Shimura & Takahara 1995, Madej & Różańska 2004). This departure is usually well described in terms of the colour temperature to effective temperature ratio. In various models this ratio varies from 1.7 - 2.0 (Shimura & Takahara 1995, Ross & Fabian 1996) to 1.8 - 2.6 (Merloni, Fabian & Ross 2000). Madej & Różańska (2004) find \( T_{col}/T_{eff} < 2 \) in their set of neutron star atmosphere models. Recent observational studies of galactic sources in...
their high states (Gierliński & Done 2004a) suggest that the
value of \( \sim 1.8 \) indeed well represents the effect. We adopt
this value in our description of the inner part of the disc
where electron scattering dominates the opacity. In the out-
most region the disc is not so strongly ionized and the
emission is expected to be close to a black body emission.
Therefore, we describe the local spectrum as
\[
F_\nu = \frac{\cos \theta}{4 \pi D^2} \int_{\theta_{\text{min}}}^{\theta_{\text{max}}} \pi B_\nu(T_{\text{eff}}) 2\pi r dr,
\]
where the effective temperature is calculated from the total
(dissipated + thermalized) flux
\[
s\sigma T_{\text{eff}}^4 = F(H, r),
\]
and to ensure the continuity between the inner and the outer
disc region, we assume
\[
T_{\text{col}}/T_{\text{eff}} = 2.228 - 0.041(r/R_{\text{Schw}}) \quad \text{if } r < 30R_{\text{Schw}}
\]
and \( T_{\text{col}} = T_{\text{eff}} \) at larger radii.

3 RESULTS

3.1 Disc shape

An exemplary shape of AGN accretion disc is shown in
Fig. 3. It is much more complex than the simple prediction
of Shakura & Sunyaev (1973) for radiation-pressure domi-
nated region. The departure is not important from the point
of view of irradiation by the extended warm absorber but it
is important for self-irradiation. Even in the innermost radia-
tion pressure dominated region the disc thickness is not
constant but rises slowly. Further out, it rises faster as the
radiation pressure drops. Some wiggling is also visible - this
is due to the complex opacities used for the description of
the vertical structure. The opacity of the outermost weakly
ionized disc region is dominated by molecules and absorp-
tion by dust, so the disc is never optically thin.

In particular, the drop in the disc height at \( \sim 3000R_{\text{Schw}} \) happens in the region of ionization instability
(Lin & Shields 1986). Here we neglect the issue of the time-
dependent disc behaviour. It is most probably justified for
high accretion rate objects since no evaporation of an inner
disc is expected and ionization instability reduces to small
flickering for a constant viscosity law (Siemiginowska, Cz-
erny & Kostyumin 1996, Janiuk et al. 2004). If the irradia-
tion by the warm absorber is included, this region is shifted
outward (see Fig. 3, dotted line). The disc thickness is in-
creased by a factor of 3 at distances \( \sim 1000R_{\text{Schw}} \) from the
black hole since irradiation was most efficient there for an
adopted model of the warm absorber. Self-irradiation (see
Fig. 3) has a very small impact on the disc thickness, visible
only at very large distances, above \( 10^6R_{\text{Schw}} \).

If accretion rate is significantly lower than used in
Fig. 3 i.e. \( \dot{m} = 0.05 \) instead of \( \dot{m} = 0.5 \) then the disc thick-
ness in the innermost (radiation pressure dominated) part is
roughly by a factor 10 smaller, the wiggle in the disc shape
(i.e. partial ionization instability region) moves in roughly
by a factor of 3, and the disc thickness in the outer region is
almost unchanged. The effect of the self-irradiation and ir-
radiation due to the scattering by the warm absorber modify
the disc thickness in roughly the same way as before.

The change in the properties of the warm absorber is
reflected in the disc thickness. Lower/higher total opacity
leads to smaller/larger increase in the disc height at dis-
tances where the irradiation is important.

The density profile of the warm absorber specifies at
which distance the irradiation is most effective (\( R_{\text{min}}, R_{\text{max}} \)
or a broad range between the two). However, performing
subsequent iterations between irradiation and the disc thick-
ness affect the final irradiation flux rather weakly.

3.2 Radial dependence of the irradiating flux

3.2.1 Direct irradiation

An example of the incident radiation flux in the absence
of the warm absorber is shown in Fig. 4 (continuous line).
Model parameters are the same as used in Fig. 3.

The flux is large at small radii, but it is nevertheless
small in comparison with the locally dissipated flux in this
region. Self-irradiation does not create energy, it only effec-
tively modifies slightly the angular dependence of the radia-
tion leaving the central region. However, as it is well known,
irradiation becomes important at large distances (e.g. Hoshi
& Inoue 1988). The sudden jump in the flux is again a con-
sequence of the rise of the disc thickness at the end of the
partial ionization zone (see Fig. 3).

Sometimes, for simplicity, the irradiation is calculated
assuming the point-like source instead of an extended inner
disc. Irradiation flux is in this approximation given by (e.g.
King 1998, King & Ritter 1998)
\[
F_{\text{inc}} = \frac{L}{4\pi r^2} \gamma,
\]
Figure 4. The irradiation flux (left panel) and the ratio of the irradiation flux to the locally dissipated flux for the same model as in Fig. 3. Continuous line - self-irradiation; dotted line - back-scattering by the warm absorber. We also show the back-scattered flux (dashed line) obtained for the warm absorber extending from $R_{\text{min}} = 100R_{\text{Schw}}$ to $R_{\text{max}} = 5000R_{\text{Schw}}$, and with the same optical depth $\tau_{\text{tot}} = 0.6$ as before. Thick horizontal line marks the region where irradiation dominates.

Figure 5. The dependence of the $\gamma$ factor on the disc radius. Continuous line: illumination by extended disc. Dashed line: point-like source approximation given by Eq. (24) for $n=1$. Long dashed line: point-like source approximation given by Eq. (24) for $n=2$. Model parameters as in Fig. 4. Negative $\gamma$ means that a point-like source located at the center would not irradiate the disc surface.

where

$$\gamma = \left(\frac{\ln h}{r}\right)^{n}(\frac{d\ln h}{d\ln r} - 1).$$

(24)

The form of Eq. (24) is general so it is illustrative to express the distribution of the irradiation flux determined from our model also as a radial dependence of the dimensionless quantity gamma. The value $n = 1$ is expected to be better for neutron star systems while $n = 2$ for black hole systems (Shakura & Sunyaev 1973, Fukue 1992, King et al. 1997).

In Fig. 5 we show both the net $\gamma$ factor which results directly from our computations and the $\gamma$ factor from Eq. (24) obtained from the disc thickness distribution in our model.

We see that the irradiation flux computed properly from the model is always positive, as expected, since the disc is irradiated at least by the nearest region. However, in these regions which are not well exposed to the innermost parts the irradiation is very small. Effective $\gamma$ factor for $\dot{m} = 0.5$ is only $\sim 2.5 \times 10^{-5}$ in the intermediate disc region, between 100 and 10000 $R_{\text{Schw}}$. It becomes larger ($\sim 0.0005$) at the distances $10^3 - 10^5 R_{\text{Schw}}$, as well as in the innermost region, approaching $\sim 0.04$ at a few $R_{\text{Schw}}$. Analytical formula (Eq. (24); dashed line in Fig. 5) does not provide a good approximation of the numerical results. Adopting $n = 2$ in this formula does not lead to better approximation - in this case the flux is generally underestimated, apart from the innermost region of a few $R_{\text{Schw}}$.

Self-irradiation of optically thick, geometrically thin disc is generally inefficient in AGN, as argued already by Tuchman et al. (1990).

3.2.2 Irradiation due to warm absorber

An example of the incident radiation flux due to warm absorber is shown in Fig. 4 (dotted line). Here we assumed the following warm absorber parameters: $R_{\text{min}} = 1000$, $R_{\text{max}} = 1200$, $\theta_{\text{max}} = \pi/3$, $\beta = 0$, $\tau_{\text{tot}} = 0.6$. In this case the irradiating flux is almost constant up to $r \approx 1000$ and falls down as $r^{-3}$ further out. Therefore, the warm absorber effectively acts as a single point-like source which captures and re-emits the fraction of the disc luminosity approximately given by $2\tau \cos \theta$, and the integration over the volume is not essential.

However, if we assume much larger extension of the
warm absorber, the effect will depend essentially on the density profile.

If the power law index describing the radial density profile, $\beta$, is close to zero the irradiation flux between $R_{\text{min}}$ and $R_{\text{max}}$ decreases roughly as $r^{-1}$, and for $\beta \approx 2$ decreases as $r^{-2}$. Below $R_{\text{min}}$ the irradiation flux is constant and above $R_{\text{max}}$ decreases as $r^{-3}$.

Generally, the irradiation by the warm absorber is negligible in the innermost part of the disc. Self-irradiation is relatively more important but not essential, in comparison with the radiation flux dissipated inside the accretion disc. At $r \approx R_{\text{min}}$, the irradiation by the warm absorber becomes dominant over self-irradiation and at a few hundred Schwarzschild radii this irradiation may dominate in the local disc energy budget. The ratio between the irradiation flux due to the warm absorber and the locally dissipated flux roughly saturates at distances larger than the outer radius of the warm absorber, and this ratio depends on the global warm absorber parameters $\tau_{\text{tot}}$, $\theta_{\text{max}}$, and $\beta$.

Since the effect of self-irradiation becomes again important in the outermost part of the disc (a few thousands Schwarzschild radii) the relative importance of the two effects depends on the adopted model parameters.

### 3.3 IR/optical/UV spectra of irradiated accretion discs

Examples of the irradiated accretion disc spectra are shown in Fig. 6. The reference model, without irradiation, is marked with dotted line. The spectrum is rather hard (blue) in the optical band. The self-irradiation of the disc changes the spectral slope only in the IR band, at wavelengths above 3 $\mu$m.

The indirect irradiation, however, may change the optical spectrum considerably. We see that assuming very slow decrease of the warm absorber density with distance we obtain spectra which are practically flat in the optical band. The disc spectrum, however, hardens again in the UV band so the effect of irradiation looks like separate spectral component. Models with larger $\beta$ still give the spectra considerably flatter in the optical range than the standard disc but the overall spectrum is practically smooth. The spectral range of this flattening depends on the adopted extension of the warm absorber.

The amplitude of the effect depends essentially on the warm absorber optical depth. If the warm absorber depth $\tau_{\text{tot}}$ is of the order of 0.1 (corresponding to the hydrogen column $N_H \approx 1.5 \times 10^{23}$ cm$^{-2}$) or less, no effect is visible and the intrinsic disc spectrum is unmodified.

For the model of the warm absorber adopted in Fig. 6, the spectral slope in the optical band $\alpha_o$ is equal to -0.88, -0.56 and -0.20 for $\beta = 0$, 0.75 and 1.5. Here the convention $F_\nu \propto \nu^{\alpha_o}$ is used. It compares interestingly with the observed slope: Laor et al. (1997) give the value $\alpha_o = -0.36$, with dispersion of 0.22, at the basis of the analysis of several PG quasars, and $\alpha_o = -0.44$ was given by Vanden Berk et al. (1991) for quasars from SDSS survey.

The assumed extension of the warm absorber also plays an important role. The dependence is the strongest if the gas density is uniform (middle panel in Fig. 6). If the outer radius is small only the UV part of the spectrum is modified while for an extended medium the modification of the UV part is weak while spectra in the optical/IR band are now much flatter. The affected spectral region is more narrow if $R_{\text{max}}/R_{\text{min}}$ is close to 1 and broader if this ratio is large.

The opening angle of the cone occupied by the warm absorber (lower panel in Fig. 6) changes mostly the overall normalization of the incident flux, similarly to the total optical depth. If this opening angle is too small ($\theta_{\text{max}} < 10^\circ$) the presence of the warm absorber has no practical effect on the disc spectrum.
We also considered other types of the warm absorber density distributions.

In one of these special cases we assumed that the density scales with the radius as \( \rho \propto \sin^2[(R/R_{\min})^{0.6}] \). Such a distribution of density waves imitates episodes of enhanced and reduced outflow. However, the resulting spectra were in practice very similar to those obtained from our power law models for \( \beta = 0 \). Integration over volume effectively smears out any distribution inhomogeneities.

In another of these special cases we assumed the geometry of the warm absorber in the form of the empty cone centered at the opening angle of 45°, as advocated for quasars by Elvis (2000). In this case the fraction of the outgoing photons intercepted by the warm absorber is very small (model described as ‘empty cone’ in the lowest panel in Fig. 6) and the change in the spectrum relatively small.

### 4 EXAMPLES OF SPECIFIC SOURCES

We choose two interesting sources for detailed modelling. Both are high Eddington luminosity objects and belong to the Narrow Line Seyfert 1 class. We do not expect an extended inner optically thin flow in this type of objects, which are analogs of the galactic X-ray sources in their soft state (Pounds et al. 1995). Broad band spectra of both sources were extensively studied. One of those, RE J1034+396 (Puchnarewicz et al. 1995, Puchnarewicz et al. 2001), was already considered as the best case of irradiated accretion disc (Soria & Puchnarewicz 2002). The other one, PG 1211+143, is argued to show the presence of the warm absorber of considerable optical depth (Pounds et al. 2003, Gierliński & Done 2004b).

#### 4.1 RE J1034+396

The observational data for RE J1034+396 (z=0.04214) was shown by Soria & Puchnarewicz (2002) and it was kindly provided by Liz Puchnarewicz. The nature of the optical/UV component is not clear; the spectra do not seem to show the narrow absorption lines typical for starlight (Puchnarewicz et al. 1995). The source is surprisingly stable in comparison to many other NLS1 galaxies (Puchnarewicz et al. 1998) although hints of variability (in timescales of a fraction of a day) are seen in the EUVE lightcurve (Halpern, Leighly & Marshall 2003). Warm absorber features were not discovered so far in this source. However, the source was observed by Chandra only for 5 ksec, and by XMM only for 15 ksec (according to [http://heasarc.gsfc.nasa.gov/](http://heasarc.gsfc.nasa.gov/)) which is not enough to detect a highly ionized warm absorber. For example, no warm absorber was seen in ASCA data and XMM for Ton S180 and even during the preliminary analysis of the Chandra data for the same source but detailed analysis of the 80 ksec Chandra data showed the presence of narrow absorption features (see Różańska et al. 2004). Therefore, the existence of highly ionized warm absorber in RE J1034+396 is not excluded.

Our model of an irradiated accretion disc well represents both optical/UV continuum and the soft X-ray spectrum (Fig. 7). The mass of the black hole, \( M = 6.3 \times 10^5 M_\odot \) is consistent with the limits \( 0.6 - 3.0 \times 10^6 M_\odot \) obtained by Soria & Puchnarewicz (2002). The object is accreting still below the Eddington ratio but close to it (\( \dot{m} = 0.84 \)). The warm absorber responsible for scattering of the inner disc emission must be quite extended (\( R_{\text{max}} = 7000 R_{\text{Schw}} \)). Such a scattering region would smear most of the intrinsic flux variability happening in the timescale shorter than a few hours. Longer trends, if present in the intrinsic flux, should be also seen as corresponding variations in the optical/UV spectrum.

ASCA and Beppo-SAX data did not show any clear effect of the warm absorber (Soria & Puchnarewicz 2002) so the warm absorber in this source, if indeed present, must be completely ionized. However, the presence of strong outflow is rather expected for sources so close to the Eddington ratio. The soft X-ray spectrum of this objects is well fitted if the disc emission is comptonized by a medium at the temperature \( T \sim 15 \) keV and optical depth \( \tau = 1.3 \) under assumption of the plane-parallel geometry (Soria & Puchnarewicz 2002). This Comptonizing medium may be identified with such outflow, as suggested by Pounds et al. (2003) in the context of PG 1211+143.

Very low value of the parameter \( \beta \) of the warm absorber results from the spectrum being very flat in \( \nu F_\nu \) plot. If a significant internal reddening is present in the source, the actual slope may be positive, and \( \beta \) larger. Mason et al. (1996) suggested the possible reddening \( E_{B-V} \sim 0.5 \) in RE J1034+396 at the basis of the \( H_\alpha \) to \( H_\beta \) ratio of 5, much higher than expected for case B recombination.

The small blue bump (Balmer continuum+blended iron lines) does not show up clearly in RE J1034+396.
Irradiation of accretion discs in active galactic nuclei due to warm absorber

4.2 PG 1211+143

The observational data for PG 1211+143 (z=0.08090) were taken from Elvis et al. (1994). This source is strongly variable and the presented data are representative for the periods when the source is bright (see e.g. Janiuk, Czerny & Madejski 2001).

The shape of the UV continuum in this object clearly indicates the presence of the small blue bump due to the Balmer continuum and blended iron lines. Such a component is present in most spectra of Seyfert galaxies. Therefore, we modelled this component and added to the resulting disc spectrum. We adopted the spectral shape of the Balmer continuum and the shape of the blended iron line component after Wills, Netzer & Wills (1985), and we assumed equal amplitude of the two components (Neugebauer et al. 1987). The overall amplitude of this component was assumed in such way that the component constitutes 37% of the total spectrum at 3000 Å and 9% at 1800 Å. The required normalization is rather typical for AGN. For example, in NCG 5548 the small blue bump accounted for up to 10% of the flux at 1840 Å and 30-40% of the flux at 2670 Å (Peterson et al. 1991, Maoz et al. 1993). The result is shown in Fig. 8.

The mass of the black hole in our model (M = 3.0 \times 10^7 M_\odot) is consistent with the limits obtained by Kaspi et al. (2000) from reverberation (M_{\text{mean}} = 4.09\pm0.96 \times 10^7 M_\odot, M_{\text{min}} = 1.21 \times 10^7 M_\odot, M_{\text{max}} = 2.36\pm0.56 \times 10^7 M_\odot), as well as with the results based on the X-ray variability (log M = 7.0 \pm 0.7 in Janiuk et al. 2001, M = 8.1 \times 10^7 M_\odot in Nikolajuk, Papadakis & Czerny 2004). The source is accreting close to the Eddington ratio (m = 0.75). The parameters of the warm absorber are consistent with requirements obtained by Pounds et al. (2003). Gierlinski & Done (2004b) presented a good representation to the broad band data, including X-ray data from XMM-Newton, by postulating an outflowing strongly ionized medium with velocity dispersion v/c \sim 0.2, which Comptonized the disc spectrum. The value of the black hole mass used in this analysis (M = 6.5 \times 10^7 M_\odot, from Boroson 2002) was somewhat higher than in our model and the Eddington ratio correspondingly higher (1.14 from Boroson 2002) since disc irradiation was not included in their analysis.

The extension of the warm absorber should greatly reduce any optical variability in this source at timescales below \sim 5 years.

4.3 Blue radio quiet quasars

Large sample of quasars obtained in course of completing Sloan Digital Sky Survey (hereafter SDSS) allowed to study the optical/UV slope distribution. The sources were divided into four classes of increasing ‘reddening’ in their spectra (Richards et al. 2003) and the composite spectra had the slope (measured between 1450 Å and 4040 Å) of -0.25, -0.41, -0.54 and -0.76, correspondingly. This sequence of spectra was well explained assuming that the effect is due to the increasing amount of reddening by amorphous carbon dust (Czerny et al. 2004). In this interpretation no irradiation of the disc seemed to be needed. However, the spectrum of the composite 1 of Richards et al. (2003), unmodified by dust, was not fully satisfactorily represented by a bare disc - clear flattening of the spectrum below log ν \approx 14.9 was visible.

We can model this flattening assuming the presence of the warm absorber. An example of solution is shown in Fig. 8. The model shows flattening at the longest wavelengths, as requested. However, we did not find a fully satisfactory representation for this high quality data - the theoretical spectrum is never quite as flat as requested by the data of Richards et al. (2003).

An alternative possibility exists - Vanden Berk et al. (2001) attributed the change of the spectral slope in the quasar composite spectrum at \sim 5000 Å to starlight contamination, at the basis of the detection of stellar absorption lines. Starburst activity may be intrinsically connected with an accretion process. A number of recent papers discuss the issue of the stars originating/existing very closely to the active nucleus and interacting directly with the accretion discs (e.g. Collin & Zahn 1999, Nayakshin 2004 and the references therein). Such a nuclear cluster may contribute to the overall spectrum. An exemplary spectrum of such a nuclear cluster (see Figure 1. of Nayakshin 2004) peaks at ν \approx 4 \times 10^{15} Hz.

We attempted to model the starlight contribution, taking the spectrum of the galaxy M31 as a template. Normalization of this contribution was a free parameter. Such a method was justified by the analysis performed by Wamsteker et al. (1990). The result is shown in Fig. 8.

The model with starlight contribution did not reproduce the quasar spectrum much better than the model of irradiated disc. It is possible that the use of M31 as template is not appropriate (see e.g. Kotilainen & Ward 1994 for the discussion of coupling between an AGN and its host galaxy), and better model of the circumnuclear cluster is needed.

Figure 8. The observational data points for PG 1211+143 and the irradiated disc model (continuous line). Parameters of the model: \dot{m} = 0.75, M = 3.0 \times 10^7 M_\odot, \nu_{\text{min}} = 0.6, \beta = 0.75, R_{\text{min}} = 100R_{\text{Schw}}, R_{\text{max}} = 5000R_{\text{Schw}}, \theta_{\text{max}} = \pi/3. Dotted line shows the disc spectrum without irradiation. Adopted cosmological model: H_0 = 75 km s^{-1}Mpc^{-1}, q_0 = 1/2.
of the model: 

\[ \dot{m} \]

The composite quasar spectrum from SDSS (Richards et al. 2003; thin continuous line), disc spectrum without irradiation (dotted line) and disc illuminated due to the presence of the warm absorber (thick continuous line). Parameters of the model: \( \dot{m} = 0.15, M = 10^9 M_\odot, \tau_{\text{max}} = 0.6, \beta = 0.75, R_{\text{min}} = 500R_{\text{Schw}}, R_{\text{max}} = 700R_{\text{Schw}}, \theta_{\text{max}} = \pi/3 \). Dashed line shows the non-irradiated disc with starlight.

If indeed all flattening at long wavelengths is due to starlight it means that the outflow of highly ionized material is either inefficient (low optical depth) or collimated.

5 DISCUSSION

The emission from a standard accretion disc was found to be a very natural model of the optical/UV spectra of AGN (Shields 1978, Czerny & Elvis 1987, Wandel & Petrosian 1988, Sun & Malkan 1989). However, spectral fits usually requested the presence of an additional underlying power law component of unspecified nature since the spectra were flatter than predicted by models, and this power law did not even seem to be connected to the power law component seen in X-ray band (Thompson 1995).

This serious weakness of the disc model caused interests in other models of the optical/UV bump like optically thin emission (Barvainis 1993). However, detection of a Balmer edge in a polarized spectrum of a quasar Ton 202 by Kishimoto, Antonucci & Blaes (2003) provided a direct evidence in the favour of the optical/UV emission originating in an optically thick medium (a disc).

However, the discrepancy between the observed optical/UV spectrum and the predictions by the canonical models remains. It is not surprising since several effects should (in principle) be included in modelling optical/UV spectra of AGN:

- cold disc evaporation in the innermost part and the transition to a hot flow
- contribution of starlight
- contribution of small blue bump (Balmer continuum and blended iron lines)
- irradiation of the cold disc by the X-ray emission from the hot optically thin plasma
- Comptonization of the disc emission by a hot plasma
- irradiation of the disc by scattered disc emission
- self-irradiation of the cold disc
- proper local models of irradiated disc atmosphere
- non-stationarity of accretion flow and of X-ray generation.

Complexity of the problem is depressing, and in many cases it is difficult to disentangle various effects. However, some help comes from analyzing broad band spectra since information about the X-ray emission provides constraints to factors modifying optical/UV band.

In the present paper we model the scattering of the disc radiation by an extended ionized medium and redirecting its emission back again towards the disc. The observational evidence of such a medium comes from the studies of warm absorbers in Seyfert galaxies (e.g. Ashton et al. 2004 and the references therein) and Broad Absorption Line (BAL) quasars (e.g. Gallagher et al. 2004 and the references therein). Observations of these objects give direct measurements of the column density of the partially ionized material, being less sensitive to the fully ionized plasma. Polarimetry observations of Seyfert 2 galaxies with hidden Broad Line Regions (Antonucci & Miller 1985; Tran 2001) and of BAL QSO (e.g. Lammey & Hutsemekers 2004) give in turn direct information about the ‘scatterers’ but at unspecified (rather large) distances from the central black hole. Estimates of the total column density of the material along the line of sight obtained from the UV studies are frequently inconsistent, and the amount of fully ionized material can be frequently underestimated. The detection rate of the warm absorber decreases with an increase of the object accretion rate (e.g. Laor et al. 1997), BAL features are seen in bright QSO. Although the connection between BAL outflow and warm absorbers is not clear they may represent basically the same outflow but of different ionization state and/or seen at different inclination angles.

This material can be traced, however, by modelling the optical/UV spectra. We show that if the warm absorber has considerable optical depth \( \tau_{\text{opt}} > 0.1 \) (or \( N_I > 10^{23} \text{ cm}^{-2} \)), and if this medium is located relatively close to the central region we can expect significant change in the optical/UV spectrum of the accretion disc in such source due to the scattering of the fraction of radiation by this warm absorber and redirecting a fraction of this emission back towards the disc. The effect depends not only on the total optical depth of the warm absorber along the line of sight but on the whole density distribution.

We considered in detail the case of a disc irradiated due to the presence of the warm absorber but we neglected disc evaporation and irradiation by hard X-ray source. We showed that the direct self-irradiation of the disc in this case is not very efficient but the indirect irradiation due to the scattering by the warm absorber may flatten the optical spectrum considerably.
In our opinion the model directly applies to high accretion rate AGN, \( m_i > 0.2 \) like quasars or Narrow Line Seyfert 1 galaxies. In those sources the disc extends practically down to the marginally stable orbit (Pounds et al. 1995, Sobolewska, Siemiginowska & Życki 2004), and an extended ADAF does not form. The hard X-ray source contains a small fraction of the source bolometric luminosity, as the optical/UV/soft X-ray Big Blue Bump strongly dominates the overall spectrum. Therefore, the irradiation by hard X-rays is energetically inefficient although it is important from the point of view of the reflection component formation. Additionally, if the hard X-ray emission comes from coronal flares and it is confined to the direct vicinity of the disk, our assumptions of emission comming from the disk surface are roughly satisfied even for this component.

We obtained satisfactory representation of the data for two NLS1 galaxies, RE J1034+396 and PG1211+143. Blue quasar composite 1 spectrum of Richards et al. (2003) is almost well represented by a standard disc, with some flattening only above \( \lambda \sim 5000 \) Å. We modelled this flattening also as the effect of irradiation due to warm absorber but the result was not quite convincing and the contribution of starlight seems to be most probable explanation.

We neglected other possible effects from our list although intrinsic reddening as well as Comptonization can strongly bias the observed FUV spectral index (Shang et al. 2004).

The irradiation of the disc due to the presence of the warm absorber may also be important in Seyfert 1 galaxies. However, typical Seyfert 1 galaxies may have their discs truncated at larger radius, and a geometrically thick inner flow develop (e.g. Poutanen, Krolik, & Ryde 1997, Chiang & Blaes 2003), the bolometric luminosity of the hard X-ray component is larger, and the source is most probably located at large distance from the equatorial plane, either corresponding to the disk truncation radius (in ADAF models), or to the position of a base of jet (Henri & Pelletier 1991; Martocchia, Matt & Karas 2002). It enhances the direct self-irradiation by the central X-ray emitting region (Chiang & Blaes 2003). So it is possible that in Seyfert galaxies both direct X-ray irradiation and indirect irradiation due to the warm absorber scattering can be equally important, but the model would include additional parameters specifying the location of the X-ray emitting plasma.

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