Matter Outflows from AGN: A Unifying Model

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Abstract

We discuss a self-consistent unified model of the matter outflows from AGNs based on a theoretical approach and involving data on AGN evolution and structure. The model includes a unified geometry, two-phase gas dynamics, radiation transfer, and absorption spectrum calculations in the UV and X-ray bands. We briefly discuss several questions about the mass sources of the flows, the covering factors, and the stability of the narrow absorption details.

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1 Introduction

There are two apparent manifestations of matter outflows from active galactic nuclei (AGN): relativistic jets observed mostly in radio-bands, and gas outflows visible in absorption in the UV and X-ray bands. The only hint of a connection of the two outflows is that the broad absorption lines are mostly observed among the radio-quiet objects, but the physical reason of this anti-correlation is unknown. Regarding the jets, there is strong support for the electromagnetic nature of the accelerating and collimating forces (Bisnovatyi-Kogan & Lovelace 2001; Blandford & Znajek 1977; Lynden-Bell 1996; Lovelace 1976; Lovelace & Romanova 2003). However, there is no common approach to the theory of absorbing outflows. Here, we discuss the outflows of the second type which were first observed in the broad absorption line quasars (BALQSO) and now are widely accepted as the physical reason for blue-shifted absorptions in both quasars and Seyfert galaxies.
The BALQSOs were discovered at the end of the 1960’s (Lynds 1967; Burbidge 1970) and have attracted increasing attention from the beginning of 1980’s (Weymann, Carswell, & Smith 1981; Turnshek 1987; Weymann et al. 1991). The intrinsic UV absorptions were observable in the optical band due to the large redshifts of the objects (z ∼ 2). Around 2000, rapid development of space telescopes brought many new results, including precise observations of absorption in the UV and X-ray bands of the AGN spectra (Crenshaw 1997; Reynolds 1997; George et al. 1998a; Kriss et al. 1995; Kriss et al. 1996; Crenshaw et al. 1998; Kaastra et a. 2000; Kaspi et al. 2000). In the new century the data regarding absorbing outflows from AGN grows quickly. Chandra and XNN-Newton have detected a wealth of absorption features (Komossa and Hasinger 2002; Netzer et al. 2003). But still there is no commonly accepted theory (or even model), which explains the physical properties, geometry, and dynamics of the absorbing flows. The X-ray spectra obtained with the new generation of telescopes appear to be more complex then those calculated with any previously considered models. As a result some emphasis has been given in recent years to empirical models and interpretations of observed properties of absorption features.

Here, we trace some the ideas and attempts at interpretation of the absorbing spectra.

The earliest theoretical models contained some general ideas, including the possible role of drag forces and cosmic rays in the dynamics of a two-phase medium (Weymann et al. 1982; Begelman, de Kool, & Sikora 1991). Most of the following dynamical models explored mainly the radiation pressure force by analogy with the theory of hot star’s wind (i.e., Lucy & Solomon 1970; Castor, Abbot & Klein 1975). Arav and Begelman (1994) considered arbitrary radial outflows, while Murray et al. (1995), Murray and Chang (1995), (1998), and Proga, Stone and Kallmann (2000) considered the flows above the surface of an accretion disk. Though the models predict UV and X-band absorptions, many questions about the structure and physics of the flow remains unanswered. The limitations of the dynamical models led to the development of purely empirical models (Elvis 2000; Ganguly et al. 2001). These were constructed to explain the wealth of observational data qualitatively without dynamical considerations. Unfortunately, all the various models do not unambiguously solve the main problems of AGN outflow physics: Where and why are the absorbing outflows generated in AGNs, and what determines the structure and dynamics of the outflows? Most of the models were built especially for interpretation of the observational data on absorption details without accounting for the full picture of the AGN structure and evolution.

In the present paper we discuss the approach to physics of the AGN outflows, referring to the well-established AGN unification and evolution model, as well as to important observational data.

The structure of the paper is as follows: In §2 we discuss relations of the evolution, unification, and mass outflow problems and present the geometrical structure of our model. In §3 we recall the main points of our model and discuss some peculiarities of a two-phase medium. In §4 sample results of the model
calculation of AGN spectra in the UV and X-ray bands are presented. Section 5 gives the main conclusions.

2 Interacting Subsystems of AGNs, Evolution and Unification Scheme

Our theoretical approach to the problem of matter outflow from AGN was presented in a series of papers by Vilkoviskij and Nosov (1994), Vilkoviskij, Karpova and Nosov (1996), Vilkoviskij and Karpova (1996), and in complete form by Vilkoviskij et al. 1999 (hereafter V99). Here, we recall the main points of this approach and discuss them in the light of new observational data. In V99 we presented the theory of BALQSO outflows based on the “interacting subsystems approach”, which supposes that the AGN consists of three main physically distinct, but strongly interacting subsystems: the central super-massive black hole (MBH); the compact stellar cluster (CSC), and the gas subsystem. The last subsystem usually includes the accretion disk (AD), the obscuring torus (OT), and the hot gas (HG) flowing within the hole of the torus. In V99 we have introduced the CSC and HG as “hidden” subsystems in the sense that there was insufficient observational data to constrain them at that time.

Now such data starts to appear, but still its interpretation remains controversial. The observational signs of high-ionization species of many elements were provided by the present generation X-ray missions XMM-Newton and Chandra, which revealed new features in the spectra of AGN. Both the emission lines from Fe XXV and Fe XXVI ions (Bianchi et al. 2004; Matt et al. 2004b) and those lines in absorption (Kaspi et al. 2002; Reeves et al. 2003; Matt et al. 2004a; Reeves et al. 2004) were observed in recent years. The interpretation of the data (Bianchi & Matt 2002; Bianchi et al. 2004; Bianchi et al. 2005) is in agreement with the orientation depended unification model with a wide distribution of temperatures of the outflowing matter, up to $T \sim 10^5-10^7$ K. Nevertheless, the interpretation is model-dependent. It depends on the assumed structure of the gas and so cannot be considered as a direct proof of the high-temperature gas. The analysis of the X-ray emission lines in NAGC 1068 (Ogle et al. 2000, 2003) lead the authors to the conclusion that the line emission dominated by warm ($T_e \sim 0.8 \times 10^5$ K), photo-ionized gas, moving with outward velocity less then 1000 km/s, possibly coincident with the narrow emission line clouds seen in the optical band. The presence of collision-ionized hot gas with $T \sim 10^7$K is restricted by the emission measure $EM < 3 \times 10^{63}$cm$^{-3}$, where $EM = V n^2$. However, the authors note that pressure confinement of the observed warm clouds requires the presence of a hot component with $T_e \sim 10^7$ K (Krolick, McKee, & Tarter 1981). So, our conclusion is that, though there are no direct evidences of the hot gas ($T \sim 10^7-10^8$ K) in the outflow, its presence is possible and it is supported by confinement and dynamical arguments discussed below.

The second subsystem postulated in V99 was the compact, massive stellar
cluster (CSC). Its mass supposed to be larger than or of the order of the central black hole mass, and its size is around several parsecs. Later, we considered the physical properties and evolution of such CSC due mainly to its interaction with the accretion disk (Vilkoviskij and Czerny 2002; hereafter VC02). We showed that the orbits of stars in the central part of the CSC tend to concentrate in the plane of the accretion disk. However, due to star-star interactions the orbits do not coincide with the accretion disk plane as found for the case of a single star (Syer, Clarke, & Rees 1991). We concluded that the mass loss from the stars crossing the accretion disk and star-star collisions could supply both the hot-gas outflow from the disk and the matter inflow to the MBH. Now the first evidence of the CSC in AGNs have been provided by recent observations of the AGNs structure with 0.1” resolution scales (Davies, Tacconi and Genzel 2004 a, b). Also, an indication of the reality of the CSC in AGNs can be seen in “relic” clusters frequently observed in the centers of “quiet” galaxies containing SMBH (Kormendy 2001) and in the stellar clusters in the centers of late-type galaxies (Boeker et al 2004).

There is substantial evidence that AGN evolution is driven mainly by intergalactic interactions and merging (e.g., Sanders et al. 1988; Menci et al. 2003, and references therein). Evidence for merged systems includes the counter-rotating galaxies (Rubin, Graham, & Kenney 1992; Kuznetsov et al. 1999). Every merging event leads to a new “duty cycle” of the AGN activity, accompanied by a starburst event in the earlier stages. The first phase of the cycle starts with the creation a new CSC by a powerful starburst in the massive dense gas cocoon around the MBH. This corresponds to the brightest IRAS galaxies.

The gas and stars in the center of the cocoon have a definite specific angular momentum. This angular momentum determines the orientation of the new accretion disk and the CSC around the central MBH. Hence, the symmetry axis of the AGN is not in general coplanar with the galactic disk. At the end of this phase, gas outflows and jets perpendicular to the disk produce polar holes in the cocoon along the symmetry axis, transforming it to a typical “obscuring torus” (OT). Then the bright AGN phase begins and it lasts about $10^7 - 10^8$ years. In this bright phase of the AGN duty cycle, the masses of the CSC and OT gradually decrease, leading to the third phase with diminishing activity corresponding to weak Seyfert nuclei and LINERs. The corresponding evolution sequence of OTs during the duty cycle is shown schematically in Figure 1 (a, b, c). It is similar to the evolution scheme derived from observations of the infrared (IR) spectra of AGNs by Haas et al. (2003).

This outlined picture of AGN evolution is compatible with the standard geometrical unification model of Antonucci (1993). The beautiful unification idea argued for the simplicity and similarity of all AGNs. But it demanded the introduction of a new important element of AGN structure, the obscuring torus (OT) (Antonucci and Miller 1985, Krolik and Begelman 1988). Nevertheless, we are still far from understanding the physical nature of OT. Obviously, the physics of the OT is connected with the existence of the compact stellar cluster produced by a starburst in the center of AGN (Wada, Norman, & Colin 2001, 2002). From the above-sketched scheme of AGN evolution, the axial hole in the
torus can naturally be produced by of the above-mentioned polar outflows of hot gas through the dusty, rotating CSC. Taking into account that the hot-gas outflow inevitably drags some cold matter from the internal surface of the OT, we conclude that the unification scheme must also include the outflow structure.

3 Unified Model of the Absorbing Mass Outflows

From the evolution scheme presented above a unified model follows. It includes both the “classical” AGN1-AGN2 unification and the absorbing outflow models. The model predicts the appearance of the spectral absorption features, the broad absorption lines in the UV, and the absorptions both in lines and continuum in the X-ray band. A sketch of the model is shown in Figure 2. The hot gas outflow, shown with radial arrows, produces a two-phase medium in the “transition layer” at the internal surface of the obscuring torus (clouds are shown with ovals and dots). The arrow marked with the “R” indicates reflected radiation.

We call the model a “Unified Outflow Model” in the sense that it is based on the standard Unification Model (Antonucci 1993) and derived the outflow properties from the unifying geometry. Taking into account this geometry, one has to consider the internal surface of the obscuring torus illuminated by the radiation flux from the central part of AGN. According to analyzes by Krolik, McKee, and Tarter (1981), Kwan and Krolik (1981), Krolick and Kriss (1995, 2001), a two-phase medium is produced at the internal surface of the OT.

We consider the dynamics of a two-phase medium consisting of cold clouds imbedded in a hot gas. Analysis of the thermal balance of the two-phase medium in the central region of AGNs shows that the temperature of the hot gas is of the order of 107 to 108 K (Kwan & Krolik 1981; Fabian et al. 1986; Sazonov, Ostriker, & Sunyaev 2004). Consequently, the electron heat conductivity is sufficiently high that the hot gas can be treated as isothermal to a first approximation. Thus the hot gas wind equation has a form close to Parker’s equation, namely,

$$\left(1 - \frac{a^2}{v^2}\right) v \frac{dv}{dr} = \frac{2a^2}{r} - \frac{GM(r)}{r^2} = g_{\text{drag}} + g_{\text{rad}},$$

(1)

where $v$ is the velocity of the hot gas, $a = \sqrt{kT/m_p}$ is the isothermal sound speed of the hot gas, and $r$ is the radial distance. The terms on the right-hand side of the equation are the accelerations due to the hot gas pressure gradient, to gravity, to the drag force from the cool clouds, and to the radiation pressure (due to the Compton scattering mainly in the hot gas).

The notable difference of equation (1) from the Parker equation is that $M(r)$ is the total mass inside the radius $r$, which is sum of the black hole mass and the distributed mass of the compact stellar cluster (CSC). Because of this the solution of the equation (1) can contain three critical points instead of one presented in the Parker solar wind equation (Vilkoviskij & Karpova 1996).
In this case the position of the trans-sonic point depends on the parameters of the equation; the most important parameter is the relation of the masses of the black hole and the CSC (Vilkoviskij et al. 1999).

The motion of the cold clouds imbedded in the hot gas is determined mainly by the radiation pressure force $F_{\text{rad}}$, the drag force $F_{\text{drag}}$ by the hot gas, and the gravitational force $F_{\text{g}}$. Thus the equation of motion of a single cloud is

$$m_{\text{cl}} \frac{dV}{dt} = F_{\text{rad}} + F_{\text{drag}} + F_{\text{g}},$$

(2)

where $m_{\text{cl}}$ is the cloud mass and $V$ is the cloud velocity, and $F_{\text{rad}} = F_{\text{lin}} + F_{\text{cont}}$ is the sum of the forces from line-scattering processes and continuum absorption due to photoionization, Compton scattering, and dust absorption.

The drag force depends on the square of the velocity difference between the cloud and the hot gas,

$$F_{\text{drag}} = \rho_{\text{hg}} S_{\text{cl}} \left[ (v(r) - V) \right],$$

(3)

where $\rho_{\text{hg}}$ is the hot gas density, and $S_{\text{cl}} = \pi \left( \frac{m_{\text{cl}}}{4/3 \mu_{\text{hg}} T_{\text{hg}} \mu_{\text{cl}} / (T_{\text{cl}} \mu_{\text{hg}})} \right)^{2/3}$ is the projected surface area of a spherical cloud. The pressure balance condition is $(\rho_{\text{cl}} / \mu_{\text{cl}}) T_{\text{cl}} = (\rho_{\text{hg}} / \mu_{\text{hg}}) T_{\text{hg}}$, where $\rho_{\text{cl}}$, $\mu_{\text{cl}}$, $T_{\text{cl}}$, and $\rho_{\text{hg}}$, $\mu_{\text{hg}}$, $T_{\text{hg}}$ are the density, molecular weight, and temperature of the cloud and the hot gas, respectively.

Calculation of absorption spectra includes two tasks: calculation of the absorption in a single cloud and calculation of the absorption in the cloudy medium. The calculation for a cloud can be divided into two steps. First we solve for the ionization radiation transfer in the cloud. This allows the calculation of the change of the intensity of the radiation with specified energy, $I(E) dE$, through the cloud and the distribution of the density of ions of the most abundant elements in the cloud, as well as the total column density of the ions $N_i$. These quantities permit us to calculate the optical depth of the cloud both in spectral lines and in the continuum. From this we can calculate the radiation transfer in the cloudy medium.

Calculation of the radiation transfer in a cloudy medium can be treated in the following way. We assume that the radiation transfer in the spectral lines is determined by resonance scattering on the ions. Also, we take into account the first scattering only, ignoring multiple scattering. This is possible due to non-spherical outflow of the cold clouds (see Fig.1).

We determine the optical depth in the $j$-th line center $\tau_j = (\pi e^2 / m_e c) (\int d\ell N_j) f_j / \Delta \nu_j$.

Here, $e$ and $m_e$ are the electron charge and mass, $\int d\ell N_j$ is the column density of the ions in the cloud (which scatter photons of the frequency $\nu_j$), $f_j$ is the oscillator strength of the transition, and $\Delta \nu_j = \nu_j v_T / c$ is the turbulent Doppler width of the line with $v_T$ the turbulent velocity and $c$ the speed of light. We suppose that the absorption line has a normalized Gauss profile $\varphi(\nu - \nu_j)$. Each cloud absorbs a fraction $1 - \exp(-\tau_j)$ of the radiation flux in the line center. Also, the clouds can shield each other. Then, the differential equation for the
radiation flux spectral density $\Phi(\nu)$ has the form
\begin{equation}
\frac{d\Phi(\nu)}{dr} = -\Phi(\nu)N_{cl}S_{cl}\left[1 - \exp\left(-\sum_j \varphi(\nu - \nu_j)\tau_j\right)\right]
\end{equation}

where $N_{cl}$ is the number of clouds per unit volume, $S_{cl}$ is the cross-section of a cloud. The probability of crossing a cloud in a distance $dr$ is $drS_{cl}N_{cl}$. The frequency which is scattered in the line center is the Doppler-shifted one relative to the spectrum of the central source, $\nu_j = \nu_{j0}\left((1 + V/c)/(1 - V/c)\right)^{1/2} \approx \nu_{j0}(1 + V/c)$, where $V$ is the velocity of the cloud, $\nu_{j0}$ is the rest frame frequency in the line center. Thus equation (4) takes into account both the filling factor and the velocity of the clouds.

A numerical code for solving the full system of equations described above has been developed by Vilkoviskij et al. (1999). The solutions for the gas dynamics and resulting spectra were obtained under the following conditions: (i) The incoming AGN spectrum consists of Planck and power-low parts and includes the broad emission lines as well. (ii) The hot gas flow is time independent. The mass flux of the cold clouds is determined with a function which typically starts from a very small value at small radii, has a maximum at the distance of the obscuring torus, and then decreases. That is, we suppose the clouds are generated due to interaction of the hot gas with the internal surface of the OT. (iii) At every step of the solution we calculate the cloud’s ionization and dynamics, and change of the radiation flux spectral intensity due to both line and continuum absorption. We take into account 374 lines, 147 ion species, and 12 of the most abundant elements.

Figure 2 shows the geometrical essence of the unification only. The unification model for an actual AGN has to include the evolutionary stage of the AGN according to the Figure 1 as well as the type of the host galaxy. In particular, the evolutionary stage is definitely related to the nature of the MgII BALQSO (the low-ionization BALQSO). There is evidence for both the influence of the orientation and for the influence of the starburst absorption in many of objects (Hines et al. 2001).

The next question related to the models of actual AGNs is the source of the mass outflows at different temperatures (the cold and warm absorbers). For example, what are the mass sources, the places, and the driving forces of the hot gas outflows?

In our view the most probable mass source of the hot gas is the hot corona above the accretion disk (Czerny & Lehto 1997; Czerny, Schwarzenberg-Czerny & Loska 1999; Kawaguchi, Shimura, & Mineshige 2001), which creates a hot gas wind. Magnetohydrodynamical driving from the surface of the accretion disk is also a likely source of the hot gas outflows (Romanova et al. 2005; Ustyugova et al. 2006). The hot gas outflow is assumed sufficiently strong that it acts to entrain cold clouds of the OT into the flow. The large clouds fragment into smaller ones which are heated and gradually evaporated, creating cold and warm absorbers (Reynolds 1997; George et al. 1998b). Of course, each cold cloud is surrounded with a warm envelope due to both heat conduction and to
its motion through the hot gas in AGN radiation field. Consequently, a multi-
phase outflow is produced along a “conical surface” with a solid angle of the
outflow corresponding to the relative fraction of sources which orb AGN1’s.

Krolik and Kriss (1995, 2001) have argued that specific conditions at the
internal surface of OT lead to the creation of a multi-phase medium due to the
evaporation of cold matter of the OT at the isobaric surface ($P = \text{const}$). Blustin
et al. (2005) investigated the properties of the warm absorbers in 17 AGNs which
produce photoelectric absorption features in the spectra of Seyfert galaxies and
BALQSOs. These are associated in most cases with the broad absorption lines
in the UV band (Crenshaw et al. 1999). Analysis of the properties of the
absorbers shows that their distances from the central engine of Seyfert galaxies
are typically close to the sizes of the OT, which supports the “multiphase torus
wind” model.

The first arguments supporting the “unified” outflow picture were based on
the results of spectropolarimetry of BALQSOs (Hines and Wills 1995; Ogle 1997;
Ogle et al., 1999). These results showed very strong polarizations (up to ~ 10\%)
in the broad absorption lines. The deeper the absorption “troughs” the stronger
the polarization. This was interpreted as a mixture of the light reflected from
the internal surface of the OT (the arrow marked “R” in Fig.2). The inclination
of the line of sight from the torus axis defines the transition from AGN1 to the
AGN2 types. A good tracer of the inclination angle is the absorption in the
X-ray band (Vron-Cetty & Vron 2000). The objects of type 1.5 (such as NGC
4151 and NGC 3516) may be examples of intermediate inclination angles (Kriss
et al., 1992).

The present unification model does not exclude the accretion disk as a source
of the obscuring matter. In particular, some properties of the models suggested
by Murray et al. (1995), Proga, Stone, and Kallmann (2000), as well as empirical
models (Elvis 2000; Ganguly et al. 2001) can provide some matter observable
in absorption. This can happen if gravitational instability or magnetic fields
strongly increase the thickness of the outer part of the accretion disk. The
“inflating” effect of an ordered magnetic field on the OT has been studied by
Lovelace, Romanova, and Biermann (1998). Further, the warping of the disk at
large distances may be important.

4 On the Dynamics of the Two-Phase Medium
and Line-Locking Interpretation

Here, we briefly discuss several problems of interpretation of the absorption
spectra in the UV and X-ray bands, which were noted by Weymann in his review
of the conference devoted to the mass-outflow problem (Weymann 2002). The
key problems are: (i) The “local covering factor.” This is the fraction of the
continuum radiation source shadowed by the absorbing gas at a defined velocity.
It has no commonly accepted interpretation (Barlow et al. 1997; Arav et al.
2002, 2003; deKool et al. 2002); (ii) Differences of the column densities derived
from X-ray and UV absorptions. Usually the latter seems to be much less (Arav
et al., 2003); (iii) Stability of the narrow details in the structured absorption
profiles of some objects, both in luminous BALQSO (Foltz et al. 1986) and
in low luminosity AGNs (Weymann et al. 1997). The brightest instances are
Q1303+308 and NGC 4151.

According to the main points of the unified model of matter outflow
described above, one has to consider the dynamics of the hot-gas outflow and the
dynamics of the cold clouds embedded in the hot gas. This was taken into
account in our model (V99). The main points of our numerical model are:

1) Spherical “cold” clouds \( T_{cl} \sim 10^4 \text{ K} \) move in the hot gas \( T_{hg} \sim 10^6−10^8 \text{ K} \) in pressure equilibrium. The acceleration of the clouds is due to the radiation
pressure both in lines and continuum. Also, we account for the drag force due to
the different speed of the hot gas and gravity.

2) The hot gas flow is driven radially by the pressure gradient acting against
gravity. The gravity is determined by both the central black hole and the
compact stellar cluster (CSC).

3) The radiation transfer is treated in the cloudy medium where only first
scatterings of photons are accounted for.

We used the equation for the change of the radiation flow \( \Phi(\nu) \) due to ab-
orption of radiation in spectral lines in the form equation (4). The equation
for continuum photoelectric absorption is:

\[
\frac{d\Phi(\nu)}{d\nu} = -\Phi(\nu)N_{cl}S_{cl}\{1 - \exp[-\tau(\nu_D)]\},
\]

(V99) where \( \nu_D = \nu(1 + V_{cl}/c) \).

Here, we consider the reason for the differences in the estimates of the column
densities resulting from the absorption features in the UV and X-ray bands.
We first estimate the dependence of the absorption on the acceleration of the
clouds. The Doppler width of a spectral line is \( \Delta \lambda = \lambda_0 V_T/c \), where \( V_T \) is the
characteristic turbulent velocity in the cloud. Letting \( a = dV/dr \), we find that
the velocity of a cloud grows from \( V \) to \( V + V_T \) in a distance \( \Delta r = V_T/(dV/dr) \).
The average number of clouds shadowing the source of the continuum radiation
(from the accretion disk) is \( N \sim n_{cl} \Delta r S_d \), where \( n_{cl} \) is the number of clouds
per unit volume and \( S_d \) is the surface area of the disk. Thus the “local covering
factor” by clouds with cross-section \( S_{cl} \) in a slab of thickness \( \Delta r \) at velocity \( V(r) \)
is \( F(V) \sim N(S_{cl}/S_d) \sim n_{cl}S_{cl}V_T/(dV/dr) \), where \( \Delta r \) is “Sobolev’s length”.
Obviously, the covering factor at a given velocity can be small when the velocity
gradient is large. Accordingly, the apparent absorption in a line will be small in
this case, even if the line absorption depth is large in every cloud. As shown by
Kwan (1990), the apparent opacity depends on the covering factor \( F(V) \) and
the single cloud opacity \( \tau_{cl} \) as

\[
\tau(V) = -\ln[\Phi(V)/\Phi_0] = \sqrt{\pi}F(V)q(\tau_{cl}) ,
\]

(6)

where

\[
q(\tau_{cl}) \sim \tau_{cl}(1 - 0.28\tau_{cl}) , \quad \text{for} \quad \tau_{cl} \ll 1 ,
\]
The situation is quite different in the case of continuum absorption, because the half-widths of the absorption bands (in the case of photoelectric absorption) are much wider than the turbulent widths of the absorption lines. This could, in principal, explain the different estimations of the column densities from UV line absorptions and the X-ray continuum absorption.

5 Line-Locking Interpretation

The dependence $\tau(V)$ of equation (6) on the velocity gradient $dV/dr$ is similar to Sobolev’s optical depth $\tau(V)$ in a moving gas. The difference is that in the system of clouds every cloud can be considered as a “macro-atom” with multiple lines. The considered dependence of the covering factor on the cloud acceleration is also related to the so-called “line-locking effect” (V99) due to the nonlinear relation of the radiation pressure force on the acceleration. Let us consider this effect qualitatively. The acceleration of clouds by radiation pressure is determined with both the line and the continuum absorption, but in the small clouds (with line opacity $\tau_{cl} < 1$), the acceleration by lines dominates ($T_d < 3 \times 10^4 \text{ K}$). The radiation acceleration by lines is typically larger than the acceleration of the hot gas. As a consequence, the clouds “out run” the hot gas (velocity $v_{hg}$). That is, they move with velocity $V > v_{hg}$, which gives rise to the drag-force $F_{\text{drag}} = \rho_{hg} S_{cl}(v_{hg} - V)|{(v_{hg} - V)}|$, acting to reduce the cloud acceleration. But if the cloud acceleration $a_{cl}$ decreases, the covering factor of the clouds (depending on acceleration, see above) can become large enough for the absorption in the strong lines to increase. Consequently, the radiation pressure force falls due to this absorption. This leads to a nonlinear change of acceleration, which can become negative. As the velocity of the hot gas increases further, it becomes higher than the cloud’s velocity at some point. Then the drag force changes sign and it acts to accelerate the clouds. This increases the radiation pressure force again, and the process repeats. The velocity dependence $V(r)$ in this case looks like a “ladder” with segments of nearly constant velocity. Figure 3 shows the velocity profile for an illustrative case. This results in the appearance of repeated narrow absorption details in the spectrum. But in this case stability of the narrow details means stability of the velocity (and acceleration) structure, and not absence of acceleration in some increased density regions of the flow as usually assumed.

We used our dynamical model to calculate the hot and cold phase gas dynamics.

Figure 4 shows the resulting calculated spectrum and the observed one for the quasar Q1303+308 (Vilkoviskij and Irwin 2001). One can see that there is rather good agreement in many details of the calculated and observed spectra. This supports the dynamical model and the above-described mechanism of “line-locking”.

Figure 5 shows in more detail that even some fine features of the calculated spectrum are similar to those observed in one of the CIV absorption throughs.
Of course, there are also differences but the agreement is satisfactory.

The main parameters of the model are: The hot gas mass flow rate, \( F = 0.1M_\odot/\text{yr} \); the black hole mass, \( M_{bh} = 1.3 \times 10^8 M_\odot \); the total mass of the compact stellar cluster, \( M_{csc} = 2.5 \times 10^9 M_\odot \); the power in the black-body component, \( L_p = 1.5 \times 1.5 \times 10^{47} \text{ erg/s} \) at the temperature \( T_p = 2.1 \times 10^4 \text{ K} \); the energy flux in the power-law continuum, \( L_{\text{cont}} = 10^{46} \text{ erg/s} \) which is assumed to have a slope of 1.7 (i.e., \( F_\nu \sim \nu^{-1.7} \)). The mass of a single cold cloud is \( 5 \times 10^{-16} M_\odot \).

The mass-flow rate contained in the small cold clouds was modeled with a linear interpolation between the following values.

| \( r(\text{pc}) \) | \( 10^{-3} \) | 2 | 10 | 20 |
|-----------------|-------------|---|----|----|
| mass flux \( M_\odot/\text{yr} \) | \( 10^{-6} \) | 0.005 | 0.6 | 0.3 |

The calculated spectrum of the same object in both UV and X-ray bands is shown in Figure 6. One can see that our model predicts the “X-ray quiet” soft X-ray spectrum as observed for BAL QSOs (Brandt, Laor, Wills 2000; Green et al. 2001).

Our present model does not include emission and absorption lines in the X-ray band. Inclusion of these is planned in the next version of the model. The spectra of AGNs are poorly known in the border of the UV and X-ray bands, where the so-called “soft excess” is present in many objects. We note that in our model the intensity of the emission lines are relatively strong relative to the continuum in the region of several tens of eV. Thus these lines can partly “mimic” the soft excess as discussed by Crummy et al. (2006).

### 6 Conclusions

As remarked by Crenshaw, Kraemer, and George (2003) “The study of intrinsic absorption is still in infancy, and detailed comparison between the observations and models has just begun”. Of course, the dynamical model which we used to calculate the Q1303+308 spectrum, involves some simplifications. Nevertheless, it is the only present-day model, which allows calculation of the spectrum with “line-locking”. The model is of course being developed further.

The mass outflow rate is a fundamental aspect of an AGN and it must be in accordance with the classical unification scheme of Antonucci (1993), which is strongly supported by observations. But a model of an actual AGN has to take into account not only the geometrical unification, but also the evolutionary stage of the AGN, the type of its host galaxy, the orientation of the accretion disk relative to the galactic disk plane, and other details. In the unified model of AGN mass outflow, the deep absorptions in the UV lines is supposed to be seen in the transition angles between the types AGN1 and AGN2. The strongest UV absorptions in Seyferts are indeed visible in the spectra of the “intermediate” types of Seyferts Sy1.5 tp Sy1.9. But more statistical investigations are needed to prove this rule.

The BAL QSOs present about 15% of radio-quiet QSOs, but the “intrinsic” fraction of BAL QSO, taking into account the K-correction, is up to 22%
(Hewett and Foltz 2003). A large part (∼ 50%) of Seyfert galaxies showing both absorption lines in UV and/or warm absorbers can be explained by larger covering factors. This is because of the smaller velocities and the velocity gradients. Partly it may reflect the larger number of high-quality spectra for the closest Seyferts. The fraction of absorbed Seyfert galaxies was estimated as ∼ 0.1 when investigated by IUE satellite with good spectral resolution.

It is possible that the internal surface of the obscuring torus is not the only source of the outflowing matter of the cool clouds. For example, the source could be the red giant winds and/or gas resulting from stellar encounters of the compact stellar cluster. Also, the absorbing gas may be present in the hollow central region of the OT due to mass outflow from the accretion disk surface. This may occur if the disk is geometrically thick in the outer region, closer to the OT due to gravitational instability and/or magnetic fields. The hydromagnetic winds from accretion disks have been studied in detail by Ustyugova et al. (1999), Romanova et al. (2004), Romanova et al. (2005), and Ustyugova et al. (2006). Hydromagnetic models for the emission and absorption properties of NGC 5548 have been developed by Bottorff et al. (1997) and Battor, Korista, and Shlosman (2000).

The above-described unified dynamical model explains many details of the complicated spectra observed in different BALQSOs. This argues for the validity of the model for the BALQSOs.

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Figure 1: Sketches of the three stages of an AGN's duty cycle.

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Figure 2: Sketch of unified AGN model (V99).
Figure 3: Dependence of the cold cloud velocity on the distance from the central object for the case discussed in §5.
Figure 4: The observed (black) and calculated (gray) spectra of the quasar q1303+308.
Figure 5: The observed (black) and calculated (gray) spectra of the quasar q1303+308 at higher resolution showing the CIV lines.
Figure 6: Predicted photon spectrum before (gray) and after (black) absorption.