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On the formation of line-driven winds near compact objects

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Abstract. The critical aspect of any radiation-driven wind theory is how the momentum is transferred from the radiation field to matter. One of the most favorable mechanism which is believed to work in winds launched from luminous accretion disks is the acceleration of plasma by the absorption of the radiation flux in lines of abundant elements. In a standard theory only gradients of the flow velocity are taken into account in Sobolev approximation, when calculating the radiation pressure force. This theory was developed to explain winds from early-type stars, for which it is in a good agreement with observational data, and now is extensively used to explain winds in AGNs, YSO, and binaries. We report on our recent studies of line-driven winds near compact objects. The crucial difference from the standard case of O-type star wind consists of the following: if a wind is settled not too far from BH (10 - 50 rg) both velocity gradient and gradient of the gravitational potential should be taken into account when calculating the radiation force. The first stands for the Sobolev effect the latter takes into account gravitational redshifting. We develop a theory of such flows from first principles, considering one dimensional wind from accretion disk around Schwarzschild BH. We show, that taking into account gravitational redshifting can indeed significantly increase the efficiency of acceleration. We discuss the possible connection of our studies with recently detected absorption features in X-ray spectra of some quasars. The observational signature of such flows may have very important implications in future studies of parameters of putative BHs in central engines.

Key words. radiation mechanisms: general – stars: mass loss – stars: winds, outflows – galaxies: active

1. Introduction

It has been demonstrated both theoretically and observationally that accretion disks around compact objects can be powerful sources of fast plasma outflows. Among the most important processes known to work are magnetic and radiation driving. In fact radiation-driven winds can exist in most of systems where accretion disk can produce enough UV radiation (the standard line-driven wind theory gives an approximate value of $L_{UV} > 10^{-4} L_{edd}$). However, this conclusion should be treated with care because of the physical conditions in a disk wind which are very different from that of an O-type star wind. While realistic accretion disk winds are most likely driven by the combination of the radiation and magnetic forces here we focus on the scenario when momentum is extracted most efficiently due to absorption of the radiation flux in lines of abundant elements.

In the paper of Dorodnitsyn (2003) (hereafter **D1**) it was proposed a mechanism when line-driven acceleration occurs in the vicinity of compact object so that the the gravitational redshifting can play an important role. The generalization of these studies in the frame of General Relativity (GR) is the problem that we address in this paper. A mechanism that we study is quite general and can be considered to work in any case when there is enough radiation to accelerate plasma and radiation driving occurs in strong gravitational field. Particularly we discuss winds in active galactic nuclei as they manifests most important properties of accretion disk + wind systems keeping in mind however that our treatment allows to consider their low mass counterparts.

It is widely accepted that a supermassive black hole (BH) lies in the cores of most of active galactic nuclei (AGN). The accretion activity around such a black hole results in a production of a powerful continuum radiation - a defining characteristic feature of the quasar phenomenon. The dynamical role of this radiation is so high that it is probably responsible for the formation of fast winds which are observed in AGN. The radiation pressure on lines plays the crucial role in acceleration of such outflows. The most prominent feature seen in about 10% of quasar spectra are the broad absorption line systems BALs - the blueshifted UV resonance lines from highly ionized species (N V, C IV, Si IV). These come from ions of differing excitation with bulk velocities of up to 0.2 c. A successful model must also explain a simultaneous existence of NALs - narrow absorption line systems (N V, C IV), seen in UV and X-rays from about a half of Seyfert galaxies and associated with outflows of 1000 $\mathrm{km\,s^{-1}}$, and BEL - broad emission lines present in all AGNs indicating flows as fast as $5 \cdot 10^3\,\mathrm{km\,s^{-1}}$. These well established features together with total luminosity of up to $L \sim 10^{46}\,\mathrm{erg\,s^{-1}}$ give us the crucial evidence of the dynamical importance of the line-driven mechanism in AGNs. A quasi-1D model of the quasar wind was developed in Murray et al. (1995) (however it is not clear how justified is the assumption that equations in radial and polar directions could be solved separately). The 2D calculations of the accretion disk powered winds were made in Proga, Stone & Drew (1998) and Proga, Stone & Kallman (2000), while the winds from massive X-ray binaries (together with ionizing effects of the radiation from the central source) have been considered in Stevens & Kallman (1990).

In the pioneering paper by Sobolev (1960), it was recognized that the problem of the radiation transfer in lines in a continuously accelerating medium is simplified drastically in comparison with that of a static case. In the paper by Lucy & Solomon (1970) it was pointed out the importance of the line opacity for the formation of winds from hot stars. Most of our understanding of the line-driven mechanism is based on the prominent paper of Castor, Abbott and Klein (1975), (hereafter CAK) where a theory of the O-type star wind was developed. These studies explained how a star that radiates only a tiny fraction of its Eddington limit, can have a very strong wind. CAK was able to demonstrate that the radiation force from en ensemble of optically thin and optically thick lines can be parameterized in terms of the local velocity gradient. This elegant theory was further developed in papers of many authors. All this work resulted in what is usually called a "standard line-driven wind theory" (hereafter SLDW).

It is rather problematic, however, to apply directly the CAK theory to accretion disk winds because of the geometrical difference and because of the different properties of the spectrum emitted by the central source of the continuum radiation. For example, a wind in AGN is likely to be launched from accretion disk-like structure and thus is intrinsically two dimensional with the geometry that is close to axial symmetry. The second crucial difference is that in active galactic nuclei a wind is exposed to a hard UV and X-ray continuum radiation that stripes electrons from abundant elements much more effectively than the quasi-black-body radiation of the hot luminous star. In case of AGN the radiation flux produces highly ionized species over much of the wind. The considerable lack of the atomic data for highly ionized ionic species and of intrinsically 2D radiation-hydro and transfer calculations makes a task of the realistic modelling of AGNs winds very problematic.

In the standard line-driven wind theory a given parcel of gas sees the matter that is upstream redshifted because of the difference in velocities (assuming that a wind is accelerating gradually). This helps a line to shift from the shadow produced by the underlying matter and to expose itself to the unattenuated continuum. It was shown in **D1**, that together with Sobolev effect the gravitational redshift of the photon's frequency should be taken into account when calculating the radiation force. In case of strong gravitational field the gradient of the gravitational potential works in the same fashion as the velocity gradient does when only Sobolev effect is taken into account, so that the radiation force becomes $g_l \sim (dv/dr + \frac{1}{c} d\phi/dr)$. As it was shown in **D1** now the gravitational field works in exposing the wind to unattenuated radiation of the central source. Thus we call such a flow "Gravitationally Exposed Flow" (GEF).

Conditions present in the inner parts of the realistic accretion disk wind are far from being clear. However it is known that most of the radiation flux is produced in the innermost parts of the accretion disk. We may expect that some part of the wind which is located beyond few tens of gravitational radii may be moving quasi-radially. To make our treatment as general as possible, we consider spherically - symmetrical radiatively accelerated wind. Lines and electron scattering are assumed to be the only sources of opacity, no ionization balance is calculated.

In **D1** gravitational field was considered by means of the gravitational potential. Thus all equations were in fact derived in the flat spacetime, and only the effect of the gravitational redshift was taken into account when calculating the radiation pressure term. The resultant solution was then compared with CAK wind solution. This approach is not self-consistent. In GR when calculating the radiation force, the effect that is due to Doppler shifting should be taken into account simultaneously with gravitational shifting (no bending of photon trajectories is considered since the force is calculated in radial streaming limit). Obviously, the CAK - type solution can exist only in the flat spacetime. It is important to note that the *self-consistent modelling* of GEF is possible only via general relativistic treatment. Thus, the main goal of this paper is to compare the general relativistic GEF solution with the SLDW solution, obtained in the Newtonian gravity.

Table 1. Table 1: Comparison of GEF solution and SLDW solution. $x_c = r_c/r_g$, $\Delta_c^{\rm GEF} = x_c^{CAK} - x_c^{\rm GEF}$. $\Delta_{\rm CAK}^{\infty} = (v_{\rm GEF}^{\infty} - v_{\rm CAK}^{\infty})/v_{\rm CAK}^{\infty}$

Model	x_c^{GEF}	$\Delta_c^{\rm CAK}$	$\Delta_{\rm CAK}^{\infty}$
s_1	15	7.47	0.57
s_2	20	9.95	0.51
s_3	50	25	0.37
s_4	100	50	0.2

Here we solve GR equations of motion for radiatively accelerated wind and calculate the radiation pressure in the radial streaming limit in the Sobolev approximation. Making use of the Sobolev approximation allows us not to treat the General Relativistic radiative transfer formalism. There exist an extensive literature, where the radiative transfer problem in GR is considered for the purpose of hydrodynamical calculations of spherically symmetric accretion (e.g. Turolla & Nobili 1988; Thorne, Flammang & Żytkow 1981; Nobili, Turolla, & Zampieri 1991). In these papers the radiative moment formalism of Thorne (1981) had been extensively used. However, for our purposes it is not needed to use this sophisticated formalism. In the Sobolev approximation the flow is treated in fact as non-relativistic and the only source of the opacity is the line and electron scattering. In such an approach it is possible to derive the radiation force without an explicit solution of the radiative transfer equation. Thus we use only escape probability arguments - exactly as the radiation force is derived in the standard line-driven wind theory (e.g. Mihalas 1978; Lamers & Cassinelli 1999)

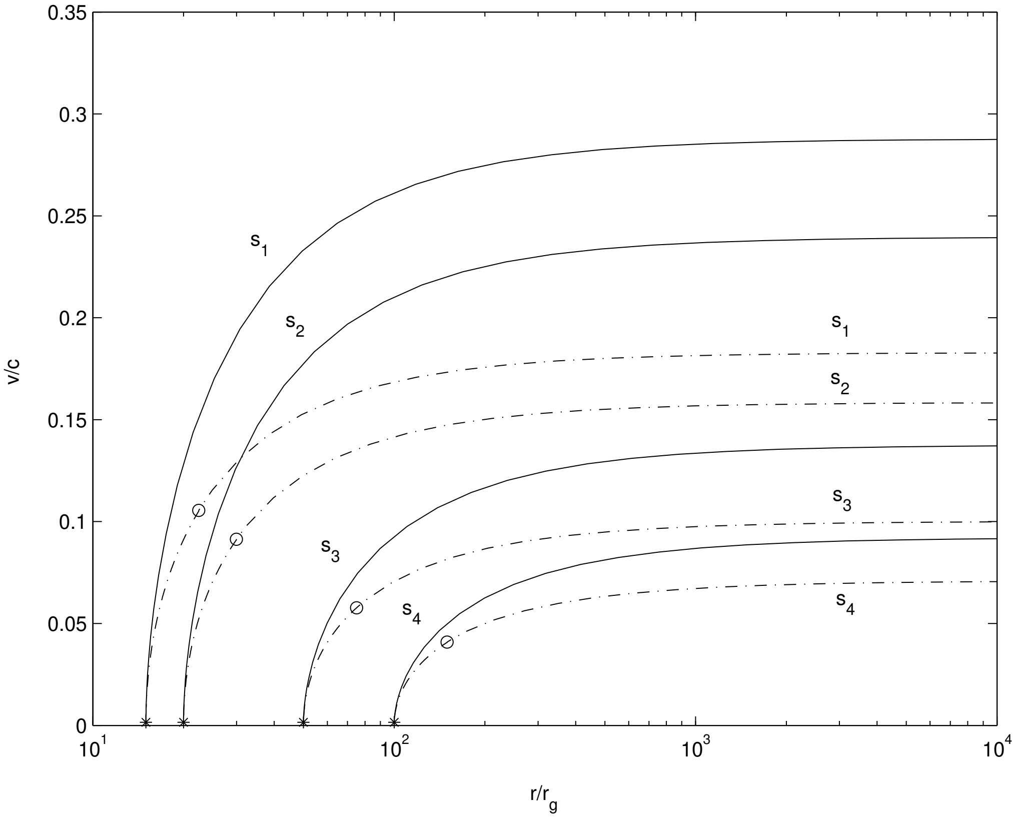

Fig. 1. Solutions of the equation of motion. Solid line - "Gravitationally Exposed Flow" (GEF) solution, dashed line - standard line-driven wind (SLDW) regime. Stars indicate GEF critical points, circles - SDLW critical points. cf. Figure 1. of Dorodnitsyn (2003) s_1 - s_4 correspond to different set of solutions.

2. Optical depth and radiation force in Sobolev approximation

A photon emitted at a given radius will suffer a continuous redshift both gravitational and Doppler and may become resonant with a line transition at some point downstream. We restrict ourself to the *radially streaming photons* only and assume that they are emitted from a point source. Sobolev optical depth between r_d and infinity is calculated for the field of *radially streaming photons* and can be represented as follows

$$t = \int_{r_d}^{\infty} \varphi(\tilde{\nu} - \nu_0)\chi_{l\nu} \frac{dr}{\sqrt{h}} = \frac{\chi_l v_{th}}{\left|\sqrt{h}\frac{dv}{dr} + \mathrm{cw}\right|}, \quad (1)$$

where $\chi_{l\nu}(\mathrm{Hz}\cdot\mathrm{cm}^{-1}) = \Delta\nu_D\chi_l$ and $h \equiv g_{00}$. , and $\mathrm{w} = \frac{d}{dr}\sqrt{h}$. If there is no gravitational redshift taken into account, then the Sobolev optical depth is obtained: $\tau_{sob} = \frac{\chi_l v_{th}}{|dv/dr|} = \chi_l\, l_{sob}$ The radiation pressure can be calculated when summing over the ensemble of optically thin and optically thick lines. Using the parameterization law of CAK we obtain the result by Dorodnitsyn & Novikov (2005):

$$g_l = \sum_l G_l = \frac{F\sigma_e}{c}\, k \left(\frac{\sigma_e \rho_0 v_{th}}{\sqrt{h}\frac{dv}{dr} + \mathrm{cw}} \right)^{-\alpha}. \quad (2)$$

where σ_e is the electron scattering opacity per unit mass and F is the radiation flux.

3. Gravitationally Exposed Flow

The equation of motion for stationary, spherically-symmetric, isothermal wind reads:

$$\frac{P+\rho}{h\rho_0}\left(vh\frac{dv}{dr}+\frac{GM}{r^2}\right)+\frac{1}{\rho_0}\frac{dP}{dr}-\frac{\sigma_e}{\sqrt{h}}\frac{L}{4\pi r^2 c}$$
$$-\frac{\sigma_e}{\sqrt{h}}\frac{L}{4\pi r^2 c}k\left(\frac{4\pi}{\sigma v_{th}\dot{M}}\right)^{\alpha}\times$$
$$\left\{\sqrt{h}\,vr^2\left[\sqrt{h}\frac{dv}{dr}+cw\right]\right\}^{\alpha}=0, \qquad (3)$$

Here we retain only terms of the order $O(v/c)$. We adopt the equation of state for the ideal gas: $P=\rho_0\mathcal{R}T$, $E_i=3/2\mathcal{R}T$, where $\mathcal{R}=k/m_p$ is the gas constant. For a given position of the critical point r_c we can calculate the value of the velocity and velocity gradient in the critical point. Adjusting the position of the critical point r_c we integrate the equation of motion inward, looking for the solution that satisfies the inner boundary condition. The qualitative picture that has been obtained in **D1** is confirmed throughout our calculations. We detect a considerable gain in terminal velocity both in comparison with CAK case and between fully relativistic calculations presented here, and semiclassical treatment of **D1**.

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