Influence of accretion disk wind on the evolution of LMX outburst

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Abstract From analysis of the light curves observed during outbursts of low-mass X-ray binaries it was found that viscosity parameter α, which characterizes the mass transport in the accretion disk within the framework of the Shakura-Sunyaev model, lies in the range of 0.2-1. However, simulations of the magnetorotational instability give values of α an order of magnitude smaller. In this work, we consider an additional source of matter transfer, namely, the wind from the disk surface. We calculate evolution of the disk taking into account the Compton-heated wind, which can decrease the value of α parameter derived from observations. As a result, we obtain the dependence of α on wind parameters. We show that the presence of wind can strongly affect the inferred value of α, as well as the entire evolution of the disk.

Keywords: Accretion, Accretion Disk, Compton-Heated Winds, Black Hole Physics, X-Ray Binary.

1. Introduction

A low mass X-ray binary (LMXB) consists of a neutron star or a black hole accreting matter from the other binary component, which usually fills its Roche lobe. In LMXB systems the donor is less massive than the compact object, and can be a main sequence star, a degenerate dwarf, or a red giant. The brightest part of the system is the accretion disk around the compact object. The orbital periods of LMXBs range from ten minutes to hundreds of days. LMXBs demonstrate repeating outbursts due to instability of disk or mass-transfer.

The matter, which transfers from the companion star, creates a cool quiescent disk. Accumulation of mass makes the disk temperature to rise. Thus, the temperature in the disk eventually reaches the value when hydrogen ionizes. The steep temperature dependence of opacity takes place in this temperature range, causing a thermal-viscous instability within the disk. During an outburst, a typical LMXB emits almost all of its radiation in X-rays, and typically less than one percent, in visible light, so LMXBs are among the brightest objects in the X-ray sky, but relatively faint in visible light.

Currently, about 18 LMXBs with a black hole are known in our Galaxy, identified by bright X-ray outbursts indicating rapid accretion episodes (see, for example, [1]). These outbursts last much longer and recur much less frequently than in many types of accreting white dwarfs, apparently due to the heating of the outer disk by X-rays emitted from the inner areas of the accretion flow.

It is believed that the magneto-rotational instability provides the physical mechanism underlying the angular momentum and mass transfer in accretion disks. The effective viscosity in the disks, usually parameterized using the α-viscosity prescription, determines the efficiency of this transportation process. Physically, the α-viscosity parameter determines the viscous time of the accretion flow and, thus, according to the disk instability picture, is encoded in the decay profile of an outburst light curve. A disk with a higher viscosity, that is, with higher α, accretes mass during an outburst faster, reducing the decay time of an outburst.

Standard model of disk accretion [2] has introduced a dimensionless viscosity parameter $\alpha \lesssim 1$, which characterizes the angular momentum transfer. Analysis of the light curves observed during LMXB outbursts demonstrates that α lies in the range of ~ 0.2–1 [3, 4]. However, modern 3-D simulations of the magnetorotational instability give values an order of magnitude smaller: $\alpha \lesssim 0.1$ [5, 6, 7].

In this work, we consider an additional source of matter and angular momentum transfer, namely, a thermal wind [8]. In the presence of the wind, the outburst characteristic time decreases mimicking the effect of large α-viscosity parameter. Thus, high α inferred from observed light curves would correspond to a smaller α if the wind operates.

2. "Compton-heated" winds

Theoretical models of accretion disks and observational data indicate that emission from the disk center may irradiate the surface of the outer disk and thus affect the accretion flow. In the standard α-model of accretion disks, the disk "flares up" in thickness in the direction of large radii, which allows the surface to be exposed to a central source of luminosity.

The heating rate per particle is proportional to the radiation intensity, but at the same time the cooling rate in the disk depends on two-particle processes and, therefore, decreases with density, that is, away from the equatorial plane of the disk. When the density drops to a critical value, the radiation heating suppresses the cooling, and the gas is heated to a high temperature determined by the interactions between the particles and photons. For X-ray binaries and quasars, the central radiation is sufficiently hard so that the gas can be heated to temperatures in excess of 10^7K, predominantly via the Compton process [8].

Following [8], let us consider a disk illuminated by X-ray or EUV continuum. The disk thickness is determined by the ratio of the sound speed to the local Keplerian speed. Above this hydrostatic scale height, the irradiated gas must either be in the hot phase, $T = T_{IC}$, where T_{IC} is the inverse Compton temperature, or be in the process of heating toward T_{IC}. The notion of escape temperature can be introduced [2]: $T_g = GM\mu/kR_0$. A hydrostatic corona may exist, if T_{IC} is less that the escape temperature. This condition is satisfied inside the radius

$$R_{IC} = \frac{GM\mu}{kT_{IC}} = \frac{1.0\times10^{10}}{T_{IC8}}\left(\frac{M}{M_{\odot}}\right) cm \quad (1)$$

where $T_{IC8} = T_{IC}/10^8$ K [8].

Furthermore, in [2], a critical luminosity is proposed:

$$L_{cr} = \frac{1}{8}\left(\frac{m_e}{\mu}\right)^{1/2}\left(\frac{m_e c^2}{kT_{IC}}\right)^{1/2} L_{Edd} = 0.030 T_{IC8}^{-1/2} L_{Edd} \quad (2)$$

where L_{Edd} is the Eddington luminosity. The ratio L/L_{cr} characterizes the effectiveness of the X-ray luminosity in overcoming gravity.

2.1. Oscillations

Instability takes place if the wind is driven by emission produced by accretion [9]. This instability leads to oscillations in the luminosity of the accretion disk, provided that the wind from the disk is strong enough. If the rate of mass loss due to wind $\dot{M}_{wind}$ is moderate in proportion to the central accretion rate $\dot{M}_a$ then the disk is stable and steady. But if $\dot{M}_{wind}$ is large enough, the flow in the disk is unstable, and the disk settles in the form of periodic oscillations [9].

3. Model

The evolution of the accretion disk is described by an equation of diffusion type [9]:

$$\frac{\partial \Sigma}{\partial t} = \frac{1}{4\pi} \frac{(GM_x)^2}{h^3} \frac{\partial^2 F}{\partial h^2} - W(h) \quad (3)$$

where Σ is the surface density of accretion disk, F is the viscous torque, $h = (GMr)^{1/2}$ is the specific angular momentum of the accreting matter, M_x is the mass of compact object, W is the function describing the wind action.

Initial and boundary conditions are required for a complete formulation of the problem of viscous evolution of a disk. In the case of accretion onto a black hole, the boundary condition at the inner boundary of the disk (corresponding to the last stable orbit) is the zero torque F. If the accretion disk is truncated by a magnetosphere of a neutron star or a young star, the internal boundary condition on F is determined by conditions at the magnetospheric boundary. Thus, in many cases, the problem has the internal boundary condition of the first kind, that is, a condition defined on the value of the unknown function. For the case of a black hole,

$$F(h_{in}, t) = 0 \quad (4)$$

The external boundary condition is important as well. In a binary system, the angular momentum is very effectively diverted by tidal forces from the outer boundary of the disk corresponding to h_{out}. Next, we assume that the mass inflow into the accretion disk proceeds only through its external boundary. Thus we obtain the boundary condition of the second kind:

$$\left(\frac{\partial F}{\partial h}\right)_{out} = \dot{M}_{out} \quad (5)$$

where $\dot{M}_{out}$ is the rate of matter inflow into the disk. Also we set the initial distribution of the viscous torque:

$$F(h,0) = F_0(h)\,, \quad (6)$$

which necessarily satisfies the boundary conditions.

We consider two types of the wind term in equation (3). In first case, for the function W we take a fitting formula for wind losses per unit area from [10] in the form:

$$W(h) = m_{ch} \times \left(\frac{1+(0.125\xi/\eta)^2}{1+(\eta^4(1+262\xi^2))^{-2}}\right)^{1/6} \times exp\,[-\left(1-(1+0.25\xi^{-2})^{-1/2}\right)^2/2\xi \quad (7)$$

where $m_{ch} = k_C \dot{M}_0/(\pi R_{out}^2)$ is the characteristic mass loss per unit area, k_C is a wind constant, $\dot{M}_0 = 2 \times 10^{18}$ g/s is the initial accretion rate on the compact object, $\xi = R/R_{IC}$ and $\eta = L/L_{cr}$. Here, we set the inflow of matter into the disk $\dot{M}_{out}$ equal to zero. The initial condition is chosen as the solution for the accretion disk at an outburst peak following Lipunova & Shakura [11].

For the wind in the second case, we use a formula from Shields et al [9]:

$$W(h) = \frac{1}{2\pi}\left(\frac{C\dot{M}_a}{ln\,(R_{out}/R_w)R^2}\right) \quad , \tag{8}$$

where R_{out} is the accretion disk radius, R_w is the wind launching radius, and $C \equiv \dot{M}_{wind}/\dot{M}_a$. In this case, we take the initial condition in the form $F \sim \dot{M}_0 \times (h - h_{in})$, where $\dot{M}_0 = \dot{M}_{out}/(1 + C)$ and $\dot{M}_{out} = 10^{18}$ g/s. Wind exists only for $R > R_w$ otherwise $W(h)$ assumed to be zero.

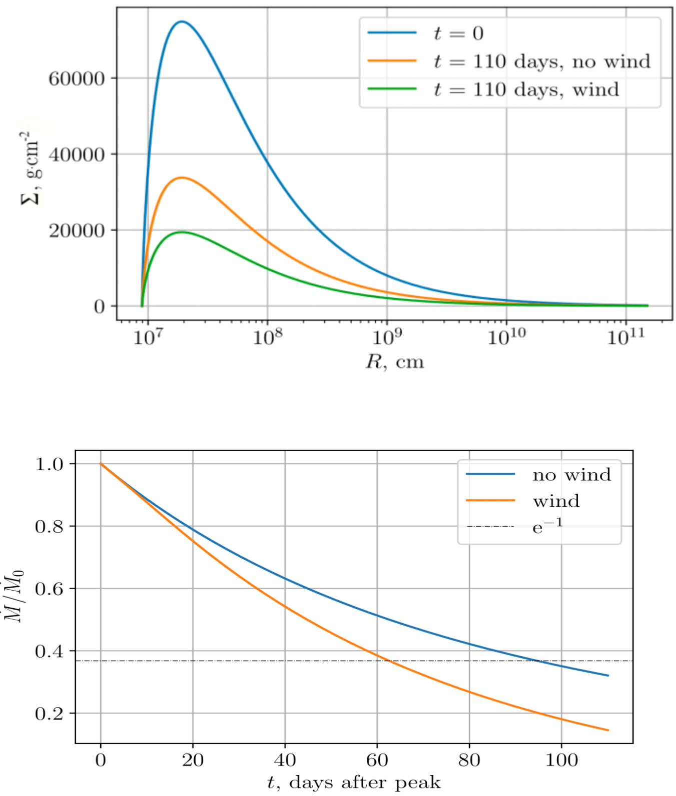

Fig1. *Evolution of accretion disk with and without wind described by equation (7). The initial condition is fixed. Upper panel: surface density versus radius. Lower panel: accretion rate on the central object. Parameters are:* *$Mx = 10 \times M_{\odot}$, outer disk radius $Rout = 1.5 \times 10^{14}$cm, kC = 3.*

4. Numerical method

Using an implicit difference scheme, we reduce the solution of differential equation (3) with the boundary conditions described in the previous section to the consequential solution of a system of algebraic equations at each time step, which is carried out by the sweep method. The implementation of the described scheme is performed using the program code FREDDI [3].

Code FREDDI calculates the evolution of the disk if it is completely ionized or if the cold front, beyond which the gas is not ionized, moves towards the center. The code is designed to simulate soft X-ray transients' light curves with fast rise and exponential decay.

The code was modified to include the wind influence on the accretion disk evolution.

5. Results

For the first type of wind (Eq. 7), dependences of the surface density on the distance from the center of the disk were calculated for different moments of time (Fig. 1, the upper panel). Dependences of the accretion rate on time, both with and without the wind, are shown in the lower panel of Fig.1.

Table1. *Mass loss and change of the decay time due to wind*

k_C	$\dot{M}_{wind}$, g/s	t_{exp}, days
0	0	94.7
0.1	8.2×10^{16}	92.9
0.3	2.46×10^{17}	89.6
1	8.2×10^{17}	80.6
3	2.46×10^{18}	62.6
10	8.2×10^{18}	39.6

Table 1 illustrates change of the decay time due to the wind effect. Here k_C is a parameter in the wind term $W(h) \sim k_C \times \dot{M}_0/(\pi R_{out}^2)$, $\dot{M}_0 = 2 \times 10^{18}, g/s$ is the initial (peak) accretion rate on the compact object, $\dot{M}_{wind}$ is the mass loss due to wind, t_{exp} is the time of the exponential decrease in accretion rate on the central object.

To verify our numerical method, we have compared results of our code with the results obtained earlier. An analytical solution for the structure of a supercritical disk with mass loss by Shakura and Sunyaev [8] was numerically successfully obtained. Also, we have reproduced the numerical results of the work of Shields et al. [9] for the accretion rate oscillations in the accretion disk with the Compton-heated wind. For this, we invoke the second type of wind (Eq. 8), which depends on the luminosity (the accretion rate on the central object). The evolution of the accretion rate is calculated (Fig. 2), which agrees well with the results presented by [9].

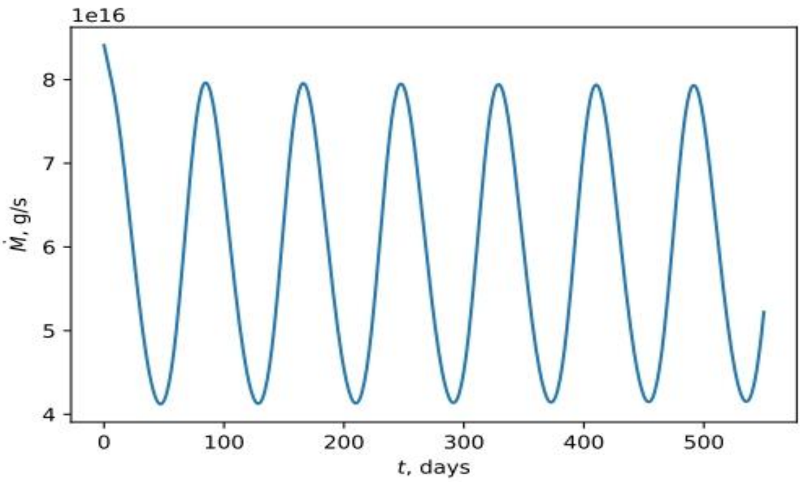

Fig2. *The time dependence of the central accretion rate for an accretion disk with wind (8) depending on the central luminosity. Here $R_w = 0.9 \times R_{out}$, $C = 15.8$. The graph clearly shows the occurrence of oscillations.*

6. Conclusion

Compton-heated winds lead to a mass loss from the disk and also remove angular momentum from it. Mass losses due to the wind can be of the order and sometimes even greater than the accretion rate onto the central object. Evidently, the winds are very significant for the accretion disk evolution if the mass loss in the wind reaches the order of the windless accretion rate. At the same time, the disk evolution speeds up remarkably.

We have verified our numerical method using the results of Shields et al [9]. Oscillations appear if the mass loss in the wind is an increasing function of the accretion rate onto the central object.

To sum up we note that a study of wind mechanisms is very important for understanding the time-dependent accretion disk behavior.

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